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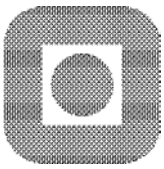

HOVEDOPPGAVE

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Fag:	Systemutvikling
Oppgavens tittel (norsk):	Annotert kallgraf
Oppgavens tittel (engelsk):	**Annotated Call Graph**

Oppgavens tekst:

En kallgraf er en rettet graf som viser relasjonene mellom prosedyrekall i et program. Nodene i grafen er prosedyrer, og kantene viser relasjonene mellom en kallende prosedyre og kalt prosedyre. En annotert kallgraf har i tillegg notasjon som viser betingelsene for at de forskjellige prosedyrene skal kalles.

Oppgaven består i å designe, implementere og teste en applikasjon som genererer den annoterte kallgrafen til programsystemer skrevet i Java. Programsystemene skal kunne bestå av mer enn en fil.

Applikasjonen skal designes slik at den kan utvides til å generere den annoterte kallgrafen til systemer skrevet i språkene C++ og C. I tillegg skal applikasjonen kunne generere forslag til testdata for den koden som analyseres.

I besvarelsen skal det også redegjøres for hvordan annoterte kallgrafer kan anvendes til test av datasystemer.

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Utført ved:	Institutt for datateknikk og informasjonsvitenskap, IME
Veileder:	Professor Tor Stålhane

Trondheim,

Faglærer

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

ANNOTATED CALL GRAPH

DEVELOPING A SYSTEM FOR AUTOMATED ANNOTATED CALL GRAPH CONSTRUCTION FOR JAVA PROGRAMS

SPRING 2002

PREFACE

This report represents our master thesis in Software Engineering at the Norwegian University of Science and Technology, Department of Computer and Information Science. Our work started in January 2002, after selecting the assignment in December 2001. We chose one of professor Stålhane's assignments. The task has been to design and implement an application that automatically generates annotated call graphs.

The result of our work is the system "Annotert Kallgraf", version 1.0, including its documentation. In addition to this report, the master thesis consists of the system, its source files and detailed design documentation on a CD-ROM. A user manual in Norwegian is also available. The manual is a more thorough introduction to the system, than the one found in this report. Since Annotert Kallgraf's user interface is in Norwegian, we decided to write the user manual in Norwegian too.

We would like to thank Professor Stålhane for his valuable guidance and feedback during the work.

Trondheim, May 21st 2002

Ulf Erik Holmen

Petter Strand

TABLE OF CONTENTS

1 ABSTRACT V

2 CONCLUSIONS VI

3 INTRODUCTION 1

3.1 DEFINITION OF THE PROBLEM 1
3.2 THE STRUCTURE OF THE REPORT 1
3.3 TEXT CONVENTIONS 2

4 CALL GRAPHS 3

4.1 INTRODUCTION 3
4.2 STATIC VS. DYNAMIC CALL GRAPHS 3
4.3 ANNOTATED CALL GRAPHS 4

5 REQUIREMENTS SPECIFICATION 6

5.1 FUNCTIONAL REQUIREMENTS 6
5.2 NON-FUNCTIONAL REQUIREMENTS 6
5.3 DOCUMENTATION REQUIREMENTS 6

6 SYSTEM DESCRIPTION 7

6.1 INTRODUCTION 7
6.1.1 Parsing and Lexing 7
6.1.2 Why Java? 8
6.2 HIGH LEVEL SYSTEM DESCRIPTION 8
6.3 DESIGN 8
6.3.1 code.Graph 11
6.3.2 code.Graph.CallGraph 11
6.3.3 code.Graph.ClassHierarchyGraph 11
6.3.4 code.PackageInterfaces 11
6.3.5 code.Parsing 12
6.3.6 code.Util 12
6.3.7 code.Visualization.Algorithms 12
6.3.8 code.Visualization.GUI 12
6.4 SPECIAL DESIGN CONSIDERATIONS 12
6.5 TESTING AND CONFORMANCE TO SPECIFICATION 13
6.5.1 Testing of Annotert Kallgraf 1.0 13
6.5.2 Conformance to Specification 13

7 ALGORITHMS 15

7.1 THE CALL GRAPH CONSTRUCTION ALGORITHM 15
7.2 THE SUGIYAMA LAYOUT ALGORITHM 16
7.3 OWN ALGORITHMS 19
7.3.1 Call Graph Construction 19
7.3.2 Class Hierarchy Graph Algorithm 22
7.3.3 Variables 26
7.3.4 Placing Text in the Vertices 28

7.3.5 The Test Data Generation Algorithm ... *29*

8 ANNOTERT KALLGRAF 1.0 ... **31**

8.1 SYMBOLS USED BY ANNOTERT KALLGRAF ... 31
8.1.1 The Class Hierarchy Graph ... *31*
8.1.2 The Call Graph ... *31*
8.2 SYSTEM FUNCTIONALITY ... 32
8.2.1 New Analysis ... *32*
8.2.2 Save Open Analysis ... *32*
8.2.3 Open Saved Analysis ... *32*
8.2.4 Close Analysis ... *33*
8.2.5 Print Preview ... *33*
8.2.6 Print ... *33*
8.2.7 Zooming ... *33*
8.2.8 Generating Test Data ... *33*
8.2.9 Copy Graph to System Clipboard ... *34*
8.2.10 Save a Graph as an Image ... *34*
8.2.11 Show Standard Java Methods and Classes ... *34*
8.2.12 Arrange Windows ... *34*
8.2.13 Help Functionality ... *34*
8.3 EXAMPLES ... 34
8.3.1 Call Graph Example 1 ... *34*
8.3.2 Call Graph Example 2 ... *35*

9 TESTING ... **37**

9.1 BLACK BOX TESTING ... 37
9.2 WHITE BOX TESTING ... 37
9.2.1 Path testing ... *37*
9.3 INTERFACE TESTING ... 38
9.4 UNIT TESTING ... 39
9.5 USE OF ANNOTERT KALLGRAF IN TESTING ... 39

10 THE SYSTEM'S USE IN RELIABILITY AND SAFETY ... **40**

10.1 RELIABILITY ... 40
10.2 SAFETY ... 42

11 FURTHER WORK ... **45**

11.1 EXTENSION TO C/C++ ... 45
11.1.1 The C Programming Language ... *45*
11.1.2 The C++ Programming Language ... *45*
11.1.3 Changes Needed for Extension to C/C++ ... *45*
11.2 EXTENSION TO TEST PATH COVERAGE ... 46
11.3 OTHER EXTENSIONS ... 46
11.3.1 Expanding and Collapsing Vertices ... *46*
11.3.2 Rapid Type Analysis ... *46*
11.3.3 Reliability ... *47*

12 REFERENCES ... **48**

13 BIBLIOGRAPHY ... **49**

14 GLOSSARY ... **50**

15 APPENDIX A 51

15.1 SYSTEM TEST ACCORDING TO TEST PLAN 51

15.1.1 The Test Plan 51

15.1.2 System Test 51

16 APPENDIX B 58

16.1 KNOWN PROBLEMS 58

16.1.1 Grammer/Parsing 58

16.1.2 Test Data Generation 58

16.1.3 User Interface 59

17 APPENDIX C 60

17.1 IMPLEMENTATION OF THE REQUIREMENTS SPECIFICATION 60

1 ABSTRACT

The main goal of this master thesis was to design, implement and test an application that automatically generates the annotated call graph of a software system. An annotated call graph shows the relations between methods in a software system, and the conditions that have to be true for a method invocation to take place. The application should be able to analyse programs written in Java.

The resulting application, Annotert Kallgraf version 1.0, allows the user to analyse several Java files. In addition to the annotated call graph, the user is presented with the class hierarchy graph and a list of all classes with their member variables and methods. Everything is presented in a Windows-based user interface. The application allows the user to print, copy, save and restore the graphs.

The annotated call graph tool might be used in testing, reliability and safety analysis. We have shown that our tool might simplify the calculation of some well-known reliability metrics, like the component complexity coefficient of Henry and Kafura, and the system reliability coefficient introduced by Cheung. It might also simplify the safety analysis of a system, because the annotated call graph combines well with fault trees. With regards to testing, Annotert Kalllgraf can generate test data for simple examples. This part of the application has, however, potential for improvement.

2 CONCLUSIONS

We have designed and implemented an application that is capable of generating the annotated call graph for programs written in Java. It also displays the class hierarchy graph of the analysed system. System functionality includes presentation, zooming and printing of the graphs. The analysed program may consist of more than one file.

The system can only generate the call graph of systems written in Java. However, it has been designed to simplify the extension to accept C and C++. For example, a graph visualization algorithm has been used to draw the class hierarchy graph, instead of a tree visualization algorithm. In Java, the class hierarchy will always be in the form of a tree, but in C++, which allows multiple inheritance, it may be a graph. Also, the graphs are built using a parser generated from a grammar specification file. The system can be adapted to support another language by changing the specification file. Thus, by replacing the Java grammar with its C++ equivalent, it is possible to generate a C++ parser, which can be integrated with the rest of the system.

Annotert Kallgraf can be beneficial in several aspects. First of all, it saves time by generating the call graph automatically. Drawing the call graph by hand is time consuming for all but simple examples. However, the user will not get the same thorough understanding of the code if the call graph is generated automatically. Secondly, the visualization of the code may give the viewer new perspectives. Especially, the ability to separate standard Java methods from other methods may prove useful. Thirdly, our tool is connected to safety, testing and reliability. Annotated call graphs facilitate the calculation of some well-known reliability measures, and makes it easier to discover and remove safety risks. Finally, the annotated call graph makes it possible to generate test data for an application. Our system can generate test data for the analysed program. The test data generation is not capable of handling complex conditions, but works for the most basic examples. It is not designed to handle conditions that include method calls and objects.

There are many possible extensions and improvements in Annotert Kallgraf. Already mentioned is the extension to support analysis of C and C++ programs. The test generation part of the application has improvement potential. When implemented, it is also possible to extend the testing to calculate test path coverage. Large graphs are slowly drawn with the current algorithms, and provide another possible improvement. This can be achieved by introducing collapsing and expanding vertices in the graph.

3 INTRODUCTION

3.1 DEFINITION OF THE PROBLEM

This assignment was originally presented by professor Stålhane as:

> *Annotated call graphs are important in safety analysis and testing. A tool for analysing C and C++ code and generating the annotated call graph is to be implemented. The graph uses fault tree notation to visualize the system. The tool will have a web-based interface that allows the user to navigate between the levels in the analysed system.*
>
> *The work can be extended to include a theoretic description of the use of call graphs in safety analysis and testing.*

During the preparations for this thesis, the assignment was rephrased. Together with professor Stålhane, we decided on the following assignment:

> *A call graph is a directed graph that shows the relations between procedures in a program. The vertices in the graph represent procedures, and the edges shows the relations between the caller and the callee. An annotated call graph also shows the conditions required for an invocation to occur.*
>
> *As part of the assignment, we will design, implement and test an application that generates the annotated call graph of systems written in Java. The analysed systems may consist of more than one file. The application will be designed to facilitate the extension to analyse files written in C and C++. In addition, the application will be able to generate test data for the analysed code.*
>
> *The report will include a chapter on the use of annotated call graphs in testing.*

3.2 THE STRUCTURE OF THE REPORT

In chapter four, we define and give an introduction to call graphs. In the fifth chapter, the requirements specification is presented. It consists of the functional, non-functional and documentation requirements.

Chapter six concerns the implemented system and its design. The high level description is found here, along with the design of the system. One section explains special design considerations we have made to simplify extension to C and C++. The chapter is concluded with test results of Annotert Kallgraf, and how it conforms to the specification.

In chapter seven the algorithms used in the implementation of the system are presented. First, algorithms developed by other people are found, followed by the most important of the ones we have developed ourselves.

Chapter eight contains information about the use of the system. The first section in this chapter explains the symbols used in the graphs. Section 8.2 gives a brief description of the most important functionality of the system. The last section presents some simple examples, including the Java code and the resulting call graph.

The ninth chapter concerns testing. After a general introduction, the use of Annotert Kallgraf in testing is detailed.

Following a chapter on safety and reliability, the report is concluded with a chapter about possible further work. Some important words are explained in the glossary in chapter 14.

3.3 TEXT CONVENTIONS

In this report we have used different fonts and layout to separate examples and important passages from the rest of the text. Code is always written in the `Courier New` font. Pseudocode or algorithms is slightly indented, while the example code fragments are separated both by indentation, horizontal bars and a numbered example heading. All code lines are numbered, and comments are written in *`gray italics`*.

4 CALL GRAPHS

4.1 INTRODUCTION

A graph is defined in [14] as:

> *A graph G(V(G), E(G)) consists of a set of vertices, denoted by V(G), and a set of edges, denoted by E(G), such that each edge connects two distinct vertices in V(G).*

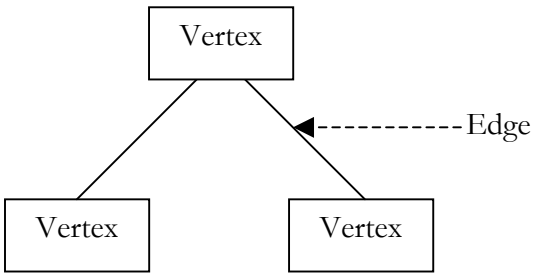


Figure 1: A graph

A graph is either directed or undirected. In a directed graph, all the edges have a specific direction, usually depicted by an arrow. In an undirected graph, there is no specification of direction. The graph in figure 1 is undirected.

A tree is defined in [15] as:

> *[…] a collection of nodes connected by edges so that there is one and only one path between any two nodes. If there is more than one path, the collection of nodes is a graph, not a tree.*

In tree-terminology a vertex is known as a node.

A call graph is defined as [2]:

> *[…] a directed graph representing the calling relationships between the methods of a program. The nodes of a call graph represent the methods in a program and the directed edges represent the caller-callee relationship.*

An annotated call graph will in addition have a notation that shows the possible conditions for the method calls.

A class hierarchy graph is a graph showing the inheritance relationships between the classes of a program. The vertices in the graph correspond to classes. An edge <a,b> shows that a is the superclass of b.

In the call graph, a vertex represents a method invocation (see figure 1). An edge symbolizes a call from one method to another.

4.2 STATIC VS. DYNAMIC CALL GRAPHS

Call graphs are either static or dynamic. A static call graph is defined in [1] as "[…] the relation describing those invocations that could be made from one entity to another in any possible execution of the program". A dynamic call graph is defined as "[…] the invocation

relation that represents a specific set of runtime executions of a program." These definitions also reflect the weaknesses of the two types of call graphs. A dynamic call graph will only show the invocations that actually take place during an execution, and does not say anything about what might happen under other circumstances. A static call graph will show all possible invocations, also those that will never take place.

Our approach, the generation of an annotated call graph, results in a static call graph. However, we remedy some of the weaknesses of static call graphs by introducing annotation. The annotation reflects the conditions that have to be true for the methods to be invoked. The downside of the annotation is increased complexity of the call graph.

4.3 ANNOTATED CALL GRAPHS

Generally, the most important benefit of a call graph is the visualization of the analysed system. It is easier to assess a visual representation of a system, than the code itself. The improved understanding of the system may also result in new ideas and approaches, which further can be used to improve the system.

The annotated call graph provides additional benefits. Annotated call graphs are especially useful in safety assessment. In safety assessment it is important to detect when and under which circumstances a method is invoked. Dynamic call graphs, however, are not likely to be used in safety analysis. The dynamic call graph shows only one possible way through the system, based on the conditions that were true for that specific execution. An annotated call graph provides information about all possibilities and the conditions for each method invocation to take place.

An annotated call graph provides a possibility for test data generation. All conditions that must be true are presented, and by using these conditions it is possible to generate test data. The test data can be used to ensure that all parts of the code have been tested for different values. Occasionally, some conditions will never be fulfilled, which in turn will result in some methods never being invoked. This knowledge can be used to simplify the analysed system.

When using Annotert Kallgraf, the user may turn off the viewing of standard Java-methods and –classes (see section 8.2.11). This possibility allows the user to discover the parts of the system that are heavily dependent on external code. It is possible for the user to remove calls to external methods from the call graph, shifting focus to the methods declared in the system. This phenomenon is also noted in [1]: "But sometimes including some unnecessary system method call can complicate the call graph and make users lose focus on other important method calls." On the other hand, the use of external code, especially class files, is a safety hazard, as you have little or no way of directly assessing the code and functionality under special circumstances.

However, the annotated call graph has some limitations. Only methods that are called from the main method, directly or indirectly, will be connected. In many cases there are methods that only will be invoked by external interaction, e.g. when the user performs an action. These methods will be visually separated from the main method. This means that you cannot remove methods that appear not to be invoked in the call graph. You must have a thorough understanding of the analysed system to be able to benefit fully from a call graph. Another drawback is the complexity of the graph. If the analysed system is of some size, the call graph is likely to be difficult to read.

There is a downside of generating call graphs automatically. Drawing a call graph by hand will increase the understanding of the analysed system. However, often there is only a small part of the call graph that is of interest, but you still have to draw the complete graph. By automatically generating the graph you can focus on the important parts, and not waste time drawing parts you know you will not use. Automatic generation also makes it easier to repeat the analysis on a changed program.

5 REQUIREMENTS SPECIFICATION

5.1 FUNCTIONAL REQUIREMENTS

F-1 The system will generate a call graph for programs written in Java
F-2 The programs can include more than one file, but the files must reside in the same directory
F-3 The system will be able to generate test data for the analysed program
F-4 The system will be able to calculate the code coverage for the test data
F-5 The system will graphically show the conditions for the method calls, if the method calls depend on conditions
F-6 The system will be able to separate standard Java methods from user-generated methods.
F-7 The users can choose whether or not they want to see the standard Java methods in the presentation
F-8 The system shall provide feedback to the user about its current operation.
F-9 The system must have a graphical user interface
F-10 It will be possible for the user to zoom in on the call graph
F-11 It will be possible for the user to zoom out on the call graph
F-12 If the user tries to analyse files that are not supported by the system (i.e. non .java-files), the system will generate an error message
F-13 The system can present the Class Hierarchy Graph of the program
F-14 For every method call, the system will give the name of the class of the object the method is called on behalf of.
F-15 Every method will exist only as one node in the graph
F-16 It must be possible to navigate horizontally in the call graph
F-17 It must be possible to navigate vertically in the call graph
F-18 If a method calls the same method several times, this will only be shown as one call in the call graph
F-19 The user shall have the opportunity to mark parts of the graph, and then print this part
F-20 If the printed part of the graph does not fit on a single page, it will be divided over several pages
F-21 The system must have a Windows-based user interface

5.2 NON-FUNCTIONAL REQUIREMENTS

NF-1 The system must be able to run under both Microsoft Windows and Unix operating systems.

5.3 DOCUMENTATION REQUIREMENTS

D-1 System documentation
General and technical documentation of the system must be generated.
D-2 User documentation
User manual and system reference must be generated

6 SYSTEM DESCRIPTION

6.1 INTRODUCTION

6.1.1 Parsing and Lexing

Parsing is the process of reading text written in some language and breaking it into primitive parts to determine its syntax. The syntax is specified in a grammar, which usually consists of several parts.

The first part is the terminals or tokens. These are the atomic symbols of the language. The second part is the non-terminals. These are variables representing the constructs in the language. The terminals and non-terminals are connected by productions or rules. Each production has a non-terminal on its left side, and a set of terminals and non-terminals as its right side, see example 1.

1 Example

The following code segment

```
1  var = var * 2
```

might correspond to the following grammar rule:

```
2  expression = expression MULT expression
```

In this grammar rule, MULT is a terminal. It corresponds to the multiplication sign, which is an atomic component of the language. `expression` is a non-terminal. The whole line is a production rule. A grammar is a set of such production rules.

The parse tree is a hierarchical representation of the grammar. All leaves in the parse tree are tokens, while all other nodes are non-terminals. Every node in the tree is based on a production. A non-leaf is based on the left side of a production. Its children represent the right side of the production.

Two different components, the lexical analyzer and the parser, perform the parsing process. The lexical analyzer, or lexer for short, reads the program text and splits it into tokens, removing white spaces and other irrelevant information in the process. In the code fragment in example 1, the lexer would separate the tokens from each other. The equality sign would be returned as a separate token, as would the variable names and the multiplication sign. The lexer returns these symbols to the parser, which tries to match the token sequence and the grammar rules. If there is no grammar rule matching the token sequence, the parser generates an error.

Constructing lexers and parsers is no simple task. Therefore several generators have been introduced. We chose to use the Java CUP [11] and JLex [10] generating tools when constructing our parser and lexer.

Java CUP
Java CUP [11] is a tool capable of generating a parser. It takes a specification file as input, and generates a parser. If the specification file only contains the grammar, the parser will state whether or not the parsing was successful. However, it is possible to state actions to be executed when a grammar rule is recognized. In our case, we build a parse tree from the grammar. For instance, every time the parser detects a method invocation, we create a new PTMethodInvocation object. The resulting parse tree works as the basis for the construction of the class hierarchy graph and the call graph.

JLex
JLex [10] is a tool capable of generating a lexical analyzer. It takes a specification file as input and generates a lexical analyser as output. The lexical analyser is written in Java.

6.1.2 Why Java?

Annotert Kallgraf was implemented using Java (JDK version 1.3.1, and some features from JDK version 1.4.0 [12]). There are several reasons why we chose Java as development language. First, the ability to run the application on different platforms is a benefit. The user can choose whether they want to run the system in Windows or Unix. We have chosen to use the platform's look and feel for Annotert Kallgraf, version 1.0, but it can easily be changed to use another look and feel. From a usability point of view, the ability to choose platform and look and feel is an advantage.

The ability to run Annotert Kallgraf through Annotert Kallgraf is another reason for choosing Java. We can generate the complete call graph for Annotert Kallgraf by analysing our own files.

The last reason for choosing Java was that only one of us has developed systems in Java earlier. On the other hand, both had previous experience in C++. Using Java gave us the opportunity to acquire new programming skills.

6.2 HIGH LEVEL SYSTEM DESCRIPTION

After the user has selected which files to analyse, the file names are sent to the parser. Here, all the files are parsed for the first time, and a parse tree is built. Then the class hierarchy graph is generated. Once this is complete, the files are parsed for the second time. Now, the goal is to produce the call graph for the analysed files. This is achieved by combining the results of the second parsing with the class hierarchy graph.

When both graphs have been generated, they are sent to the visualization part of the application. The visual appearance of the graphs is improved by applying a positioning algorithm. When the positioning of the vertices of the graphs is complete, they are drawn in the graphical user interface.

6.3 DESIGN

In this section, the packages that make up Annotert Kallgraf are presented briefly. The complete design documentation can be found on the Annotert Kallgraf CD-ROM.

The system consists of two parts. The first part is the graph generation. In this part, the source files are parsed, and the class hierarchy graph and the call graph are generated in

memory. In the second part, which is visualization, the graphs are displayed to the user. The application consists of five main packages. Their names and relations are shown in figure 2.

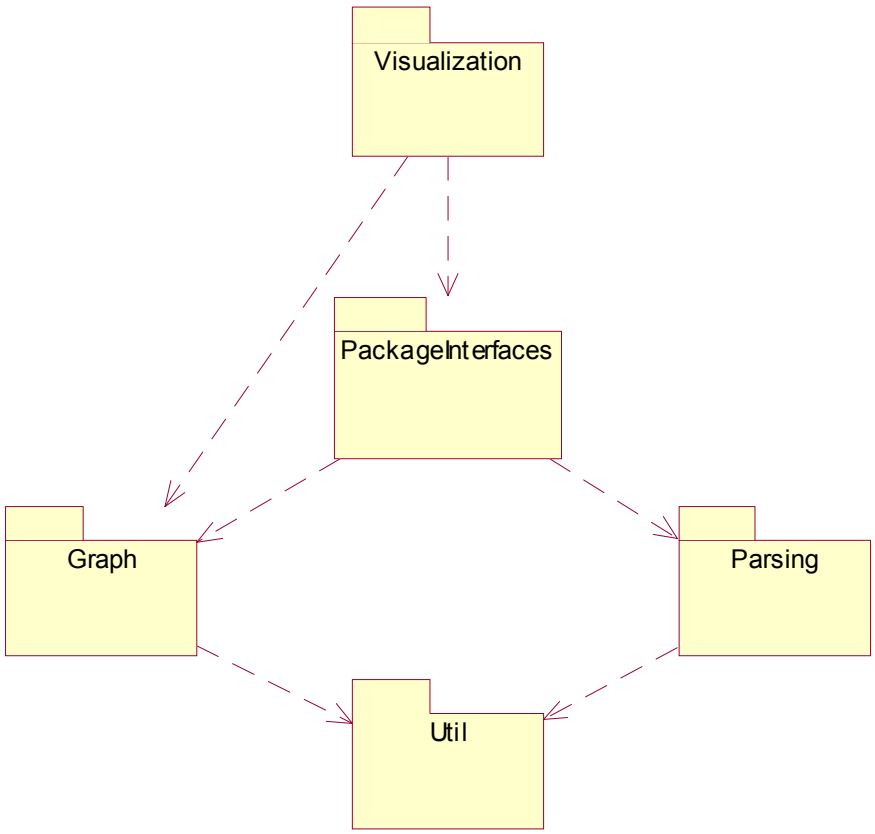


Figure 2: The packages and their relationship

The Visualization package constitutes the visualization part of the system. The PackageInterfaces package provides an interface between Visualization and the rest of the packages, which make up the graph generation part.

The Parsing package contains all classes necessary for parsing the files and building the parse tree. The Graph package contains the tools necessary to build the two graphs of the application: The class hierarchy graph and the call graph. Each graph has its own sub-package inside code.Graph, as shown in figure 3.

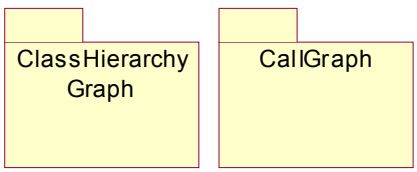


Figure 3: The sub-packages in the Graph package

The Util package contains utility classes that are used by both Parsing and Graph.

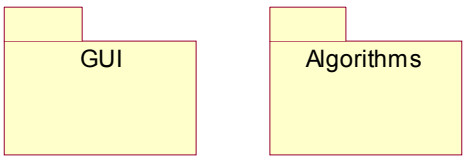


Figure 4: The sub-packages in Visualization

The Visualization package consists of two sub-packages, as shown in figure 4. Visualization.GUI consists of all classes necessary to build the graphical user interface of the program. Visualization.Algorithms contains two classes that implement the visualization algorithm for the graphs.

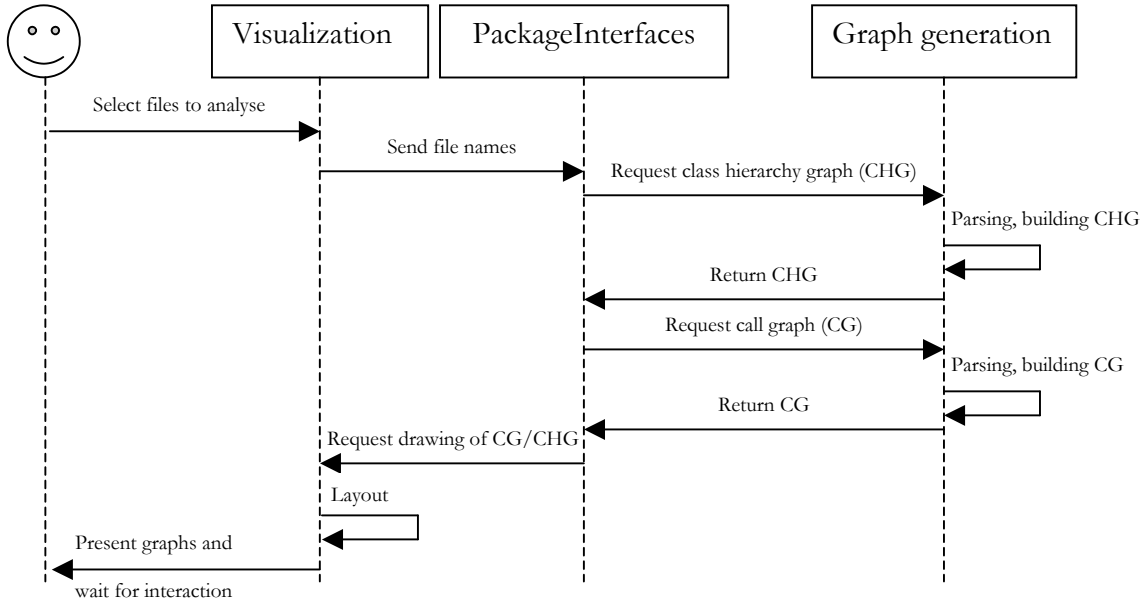


Figure 5: An overview of the system with the visualization and graph generation part and the interface between them

PackageInterfaces contains two classes, VisualizationInterface and GraphInterface. These two classes create the interface between the Visualization and graph generation packages. The idea is that the communication between the two main parts of the program shall go through the interface classes, see figure 5. If a class in the visualization part wants to access the graphs, it does so via the VisualInterface and GraphInterface classes. Thus, PackageInterfaces provides an interface between the two parts of the program. However, there are some method calls that do not go through the interface. The positioning and drawing functionality is called from the Visualization package, without passing through the interfaces. Despite this inconsistency, there are several reasons for keeping the interface:

1. The PackageInterface is a convenient place to keep the methods that generate the graphs. The responsibility for showing the generated graphs is also placed here.

2. The use of an interface provides a separation of the two different parts of the system, the graphs and the visualization. This has been a great benefit during the development, testing and fault detection of the application. We have had the possibility to look separately at the graph generation part of the system.

3. Much of the communication between the two main parts goes through the interface, and this improves the structure and organization of the application. If the interfaces were removed, lots of classes would invoke each other's methods directly, thus making the structure more complex. On the other hand, forcing all method calls to pass through VisualInterface and GraphInterface would reduce the speed of the application. For example, the graphs are displayed by invoking the paint method of each vertex. This functionality is not channelled through the classes in PackageInterfaces. If the drawing functionality were to be channelled through the interface, there would be a large increase of method calls, and a speed reduction in the system.

6.3.1 code.Graph

This package contains classes that are necessary to model a graph. There are three classes in the package:

- Vertex, which models a vertex in the graph
- Edge, which models an edge between two vertices
- GraphInformation, which stores information about a graph.

6.3.2 code.Graph.CallGraph

This package contains classes that are specific for the call graph. Many of the classes in this package are subclasses of equivalent classes in code.Graph. The functionality that is specific for the call graph is the following:

- There are two types of vertices: The invocation vertex and the condition vertex. Each of these types has its own class. Both are subclasses of code.Graph.Vertex.
- When calculating the test data coverage, it is essential to distinguish between different types of edges. This is taken care of by the class CGGraph, which is a subclass of code.Graph.GraphInformation.

6.3.3 code.Graph.ClassHierarchyGraph

This package contains information that is special for the class hierarchy graph. Some of the classes in this package are tightly connected to the classes in code.Graph through inheritance:

- CHGGraph is a subclass of code.Graph.GraphInformation. It contains the logic necessary to create the class hierarchy graph.
- CHGClassNode is a subclass of code.Graph.Vertex. This class models a vertex in the class hierarchy graph.

6.3.4 code.PackageInterfaces

PackageInterfaces contains two classes that work as glue between the different packages of the system:

- GraphInterface is the interface to the graph generating part of the system. This class instantiates the parser, orders the parse tree to create the class hierarchy graph, and generates the call graph.
- VisualInterface is the interface to the graphical user interface of the application. This class builds the graph specific parts of the graphical user interface, and manages the visualization of the graphs.

6.3.5 code.Parsing

This package consists of all the classes that are necessary to build a parse tree. We have used JLex [10] and Java CUP [11] to generate two of the classes in this package. These two classes are the parser and lexer of the application. The rest of the package consists of classes that are nodes in the parse tree. These classes have a common super class, code.Parsing.PTNode.

6.3.6 code.Util

Two utility classes have been placed here:

- UTILVariableStack is a stack that is used for organizing the local variable declarations.
- UTILNodeVector is a Vector that works as a temporary storage for class graph vertices. It is used when building the class hierarchy graph.

The classes in this package are related to the code.Parsing and code.Graph.ClassHierarchy packages. The parse tree nodes use the UTILVariableStack to store local variable declarations, see section 7.3.3 for the use of this class. UTILNodeVector is used by the class code.Graph.ClassHierarchyGraph.CHGGraph to generate the class hierarchy graph, see section 7.3.2 for details.

6.3.7 code.Visualization.Algorithms

Two algorithms that are used in graph visualization are placed here. They are implemented in their own classes:

- ALGOSugiyama implements the Sugiyama layout algorithm, which is explained in section 7.2.
- ALGODoubleArraySorter sorts a double array by using the QuickSort algorithm. This class is used by ALGOSugiyama to position a graph.

6.3.8 code.Visualization.GUI

This package contains the classes that constitute the graphical user interface of the application. All user actions are dealt with here, and responsibility is delegated to the different packages. When the user starts a new analysis, the GUI package will contact the code.PackageInterfaces package with the request. The classes in the GUI package will present the returned result.

6.4 SPECIAL DESIGN CONSIDERATIONS

Annotert Kallgraf version 1.0 supports only analysis of files written in Java. We have made the extension to other languages simpler by making the following design decisions:

- The classes in the Parsing package have been designed in a general and object-oriented way. This means that these classes are easily applicable to other languages, and it is also easy to add new classes to this package, thus making the transition to other programming languages easy.
- There are two important methods in the parse tree classes. The first is generating the class hierarchy graph. The other is generating the information necessary to build the call graph. Both these methods are recursive. In addition, the implementations of these methods have mostly the same signatures in all classes.

This means that it is easy to implement these functions in new classes that are introduced.

- We have implemented the graph visualization algorithm of Sugiyama. All graphs are displayed using this algorithm. When displaying the Java class hierarchy graph, Sugiyama is not strictly necessary. In Java, multiple inheritance is not allowed. Therefore, each class has only one parent, and the class hierarchy is a tree (see section 4.1 for details). Many tree visualization algorithms would display the class hierarchy faster, and more visually pleasing, than the Sugiyama algorithm. We have used the Sugiyama algorithm because it makes extensions easier. When displaying the C++ class hierarchy graph, one must use a graph visualization algorithm, because multiple inheritance is allowed. If we had used a tree visualization algorithm to display the class hierarchy graph, this algorithm would have to be removed to allow C++ class graphs, thus making extensions more difficult.
- Inside the PTNode class, we have implemented a vector containing the basic data types of the Java language. This Vector is used when determining the types of the parameters of a Java method. Likewise, the basic data types of C/C++ can be stored in a similar vector.
- The building of the graphs is based on the use of a parser that is constructed from a Java grammar. By changing the grammar, one can easily generate a parser for a new language. The only thing that is needed is a grammar for this language. This means that constructing a new parser is a relatively simple task.

6.5 TESTING AND CONFORMANCE TO SPECIFICATION

6.5.1 Testing of Annotert Kallgraf 1.0

Annotert Kallgraf 1.0 has been tested frequently during development. In addition, we have tested the system after it was finished. In Appendix A, a full system test according to the specification is presented.

We have also tested the system by running all its files through Annotert Kallgraf at once (approximately 15.000 lines of code). We had to keep the parser-generated files out of the test, due to use of special characters in those files (see known problems in section 16.1). The system was able to generate the class hierarchy graph and call graph for all these files. The execution took about 30 minutes and resulted in a call graph with approximately 1.600 vertices.

6.5.2 Conformance to Specification

Annotert Kallgraf version 1.0 conforms to the specification presented in chapter 5. Every requirement has been fulfilled. In the following we have made some remarks regarding the conformance to the specification.

F-2 *The programs can include more than one file, but the files must reside in the same directory*
In addition to analyse files in the same directory, Annotert Kallgraf is able to analyse the files in the given directory and in all sub-directories.

F-3 *The system will be able to generate test data for the analysed program*
The system is able to generate test data for relatively simple constructs. There are, however, quite a few shortcomings in the test data generation, se section 16.1.2 for details.

F-4 *The system will be able to calculate the test code coverage for the test data*
The calculation of the test code coverage is not always correct.

F-13 *The system can present the Class Hierarchy Graph of the program*
The class hierarchy graph is always shown (or at least available).

F-16 *It must be possible to navigate horizontally in the call graph*
In some cases when zooming in or out, the scrollbars may be shown wrong. As a result some parts of the graphs may be unreachable, thus it is impossible to navigate horizontally. This can, however, easily be remedied by the user by resizing the graph window when this situation occurs. This problem (and solution) also applies to requirement F-17.

F-20 *If the printed part of the graph does not fit on a single page, it will be divided on several pages*
Some pages that are printed may be blank. The graph drawing does not cover all parts of the drawing context. When printing, the graph is divided into areas that fit on one page. All these areas are printed; including those that do not contain any information.

NF-1 *The system must be able to run under both Microsoft Windows and Unix operating systems.*
The application was designed, developed and tested in Windows. The installation program is available for Windows only and the user guide is written with Windows in mind. However, Annotert Kallgraf is tested and will run under Unix as well.

In Appendix B a list of known problems is presented. In Appendix C, we have given an overview of the connection between functional requirement and the different classes in Annotert Kallgraf. The overview is intended to assist during possible extension of the system.

7 ALGORITHMS

7.1 THE CALL GRAPH CONSTRUCTION ALGORITHM

Name
Call Graph Construction

Developed by
Bairagi, Kumar and Agrawal, North Carolina State University [2]

File
code.PackageInterfaces.GraphInterface

Purpose
Constructing a precise call graph by exploiting the static class hierarchy of an object oriented program.

Prerequisites
None

The algorithm
Phase 1 – Build the class hierarchy graph
Our version of this phase is described in the section 7.3.2.

Phase 2 - Information collection phase
The objective of this phase is to collect information about the methods in the program, and the call sites inside every method. This information is stored in a hash table. The key to the hash table is the combination of class name and method name. In order to store the information, we need to build a data structure containing the following data items:

- the method signature
- a list of call sites inside the method.

Algorithm
Every time we locate a method declaration, we build a data structure containing the method signature. For every method call inside the method declaration, we store call site information, e.g

- the list of actual parameters
- the type of the object
- the name of the method.

The call site information is added to the data structure. Then the structure is added to the hash table. The algorithm in this phase is continued until every method inside every class has been added.

Phase 3 - Building the call graph
The objective of this phase is to build the call graph. The information about every method declaration in the program has already been stored in phase 2. Every method declaration also contains a list of its method invocations. In order to fulfill this phase, we need to have

a data structure that contains the call graph. The call graph is made up of a set of vertices and edges.

Algorithm
The first operation is to create a list of method declarations. At the initial stage, the main method declaration is added to the list. The algorithm then progresses by performing the following steps, until the list is empty:

1. Retrieve the last element from the list
2. Retrieve the list of call sites from the element
3. For every call site, there are two possibilities
   i. The method is not declared in the class of the object. In this case, the algorithm progresses up the class hierarchy graph, until a corresponding method declaration is found. The name of the class that contains the declaration is stored.
   ii. The method is declared inside the class of the object. The algorithm does nothing
4. If the vertex with the given class and method name has not yet been created, create it and add it to the list of method declarations.
5. Add the edge linking the element retrieved in 1, and the method declaration to the call graph.

Phase 3 was used as inspiration when we developed our own algorithm for constructing the call graph. Our version is presented in section 7.3.1.

7.2 THE SUGIYAMA LAYOUT ALGORITHM

Name
The Sugiyama Layout Algorithm

Developed by
K. Sugiyama, S. Tagawa, and M. Toda [4], our implementation is mainly based on Wenbin Ma's work [9]

File
code.Visualization.Algorithms.ALGOSugiyama

Purpose
The purpose of the algorithm is to order the vertices in the call graph to increase readability.

Prerequisites
Each vertex must have a unique identifier. This is implemented by using a static integer member variable in the class Vertex.

The Algorithm
The Sugiyama algorithm distributes the vertices of a graph on different levels, and sorts the vertices inside the levels. The final result of Sugiyama is that each vertex is assigned a unique location in the graph. The algorithm is minimizing the edge crossings when distributing the vertices.

The algorithm:

1. Store the unique identifiers of each vertex
2. Store the edges of the graph.

3. Store the neighbour relations between the vertices, i.e. which vertices are edged to other vertices.
4. Store the positions of every vertex. Initially, all positions are (0,0) (the upper left corner of the window).
5. Assign a level to every vertex, and adjust their positions accordingly.
6. Sort the vertices inside each level by performing the barycenter algorithm. The barycenter algorithm compares pairs of levels at the time. The positions of the vertices at one level are fixed, whereas the vertices at the other are sorted. The objective of the sorting is to reduce the number of edge crossings.
   The algorithm executes the following for loop:

```
2  FOR(every level in the graph)
3  BEGIN
4    FOR(0 UNTIL 2)
5    BEGIN
6      IF(level is greater than 0)
7        Perform up-barycenter
8      IF(level is less than total level)
9        Perform down-barycenter
10   END
11 END
```

The Barycenter Algorithm

The vertices on the fixed level are assigned values, starting at 1 at the leftmost vertex; its right neighbour gets 2 and so on. Every vertex on the non-fixed level will then have an average value depending on which other vertices it is connected to, e.g. a vertex that is connected to vertex 1 and 3 on the fixed level will have an average value of 2.

Up-barycenter

Up-barycenter keeps the vertices on the top level (of two given levels) fixed, while the level below is the one that is to be sorted. The values are assigned to the top level, and the average value is calculated for the bottom level, as shown in figure 6.

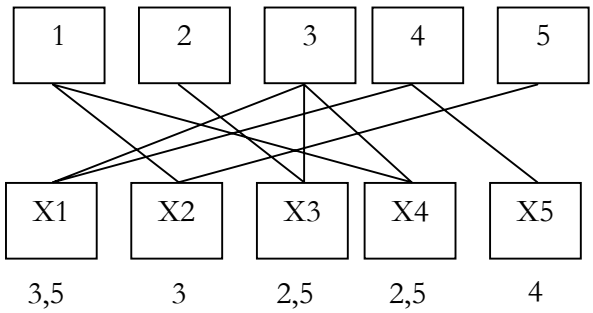


Figure 6: Up-barycenter, first step

In the second step of the algorithm, the vertices on the bottom levels are sorted. The sorting is based on the average values, and the vertex with the lowest average value is placed at the leftmost position. Then the other vertices are placed by an increasing average value, see figure 7.

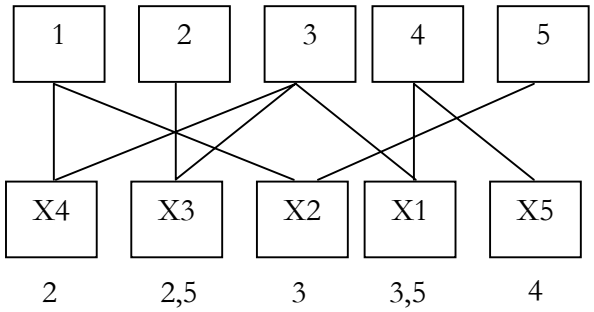


Figure 7: Up-barycenter, second step

Down-barycenter

In the case of down-barycenter sorting, the principle is the same as for up-barycenter. The only difference is that this time the lower level is kept fixed, while the top level is sorted according to the average value, see figures 8 and 9.

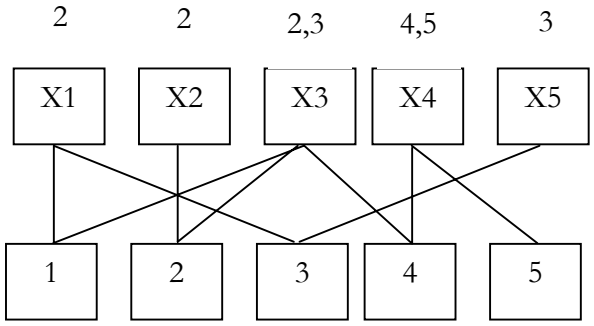


Figure 8: Down-barycenter, step one

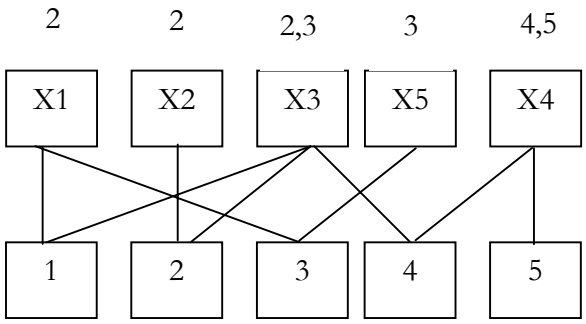


Figure 9: Down-barycenter, second step

7.3 OWN ALGORITHMS

In this section we present some of the algorithms that we have developed during the implementation of Annotert Kallgraf.

7.3.1 Call Graph Construction

Name
Call Graph Construction

Developed by
This algorithm is an extended version of the one described in phase 3 in section 7.1, and was developed by Holmen and Strand

File
code.PackageInterfaces.GraphInterface

Purpose
To modify the algorithm presented in [2] to fit our needs for call graph construction.

Prerequisites
The basis of this algorithm consists of several classes:

code.Graph.GraphInformation
This class stores the edges and vertices in a graph. It has one subclass in each of the packages code.Graph.CallGraph and code.Graph.ClassHierarchyGraph

code.Graph.Edge
This class models an edge between two vertices.

Code.Graph.Vertex
The class models a vertex in the call graph. It is subclassed in three classes: code.Graph.CallGraph.CGInvocationVertex,
code.Graph.CallGraph.CGConditionVertex and
code.Graph.ClassHierachyGraph.CHGClassNode

We have also created a class that corresponds to the data structure described in section 7.1. This class is called CGMethodDeclaration, and contains the following data items:

- the name of the class
- the name of the method
- a list of formal parameters
- a list of the call sites in the method. Each call site is an object of type CGMethodInvocation. Each CGMethodInvocation contains a list of its corresponding conditions.

Phase 2 (information collection phase) in the algorithm presented in 7.1 is similar to our. As a result, the objects of type CGMethodDeclaration have been stored in a hash table.

Our phase three algorithm is described in pseudo code below.

The algorithm

1. Retrieve the signatures of all main methods in the system.
2. For every main method: Fetch the CGMethodDeclaration that contains the main method. These objects are retrieved from a hash table that contains all method declarations in the program
3. Create a linked list called worklist. This list stores the CGMethodDeclarations as they are fetched from the hash table. Store the CGMethodDeclarations from 2 in worklist.
4. Retrieve all non—main methods and store them in the worklist.
5. Create a new object of type CGCallGraph, and call it callgraph.
6. Step through the following while loop:

```
12 WHILE(worklist not empty)
13 BEGIN
14   /*
15   Fetch the last element in worklist. This element
16   is of type CGMethodDeclaration. Call this object obj1
17   */
18   CGMethodDeclaration obj1 = worklist.lastElement();
19   /*
20   Create a CGInvocationVertex object. Initialise it
21   with the class name and method name from
22   CGMethodDeclaration. Call the CGInvocationVertex object
23   vertex1
24   */
25   vertex1 = new CGInvocationVertex(obj1);
26   IF(vertex1 is not stored in callgraph)
27   BEGIN
28     Store vertex1 in callgraph
29     Remove the last element from worklist.
30   END
31   /*
32   Retrieve the list of method calls from the
33   CGMethodDeclaration object. Call this list methodCalls.
34   */
35   LinkedList methodCalls = obj1.getCalls();
36   FOR(every method call in methodCalls)
37   BEGIN
38     /*
39     Retrieve the first element from the list of method
40     calls. Every element is of type CGMethodInvocation
41     */
42     CGMethodInvocation invoc=methodCalls.firstElement();
43     /*
44     Create a CGInvocationVertex based on the
45     information in the list element.  Call this
46     object vertex2.
47     */
48     vertex2 = new CGInvocationVertex(invoc);
49     IF(callgraph does not contain vertex2)
50     BEGIN
51       Add vertex2 to callgraph
52     END
53     /*
54     Retrieve the linked list containing the conditions
55     from invoc. Call this object conditions
56     */
57     LinkedList conditions = invoc.getConditions();
58     IF(conditions is an empty linked list)
```

```
59      BEGIN
60        /*
61        Create an Edge object linking vertex1
62        and vertex2. Call this object edge1.
63        Add edge1 to callgraph.
64        */
65        edge1 = new Edge(vertex1,vertex2);
66        callgraph.addEdge(edge1);
67      END
68      ELSE //conditions is non-empty
69      BEGIN
70        IF(only one condition)
71        BEGIN
72          IF(condition NOT in callgraph)
73          BEGIN
74            /*
75            Create a CGConditionVertex based on the
76            only element in conditions, and add it to
77            the callgraph
78            */
79            cond = new CGConditionVertex(conditions(0));
80            callgraph.addVertex(cond);
81            // Link the first vertex with the condition
82            edge1 = new Edge(vertex1,condVertex);
83            // Link condition with the second vertex
84            edge2 = new Edge(condVertex,vertex2);
85            // add them to the callgraph
86            callgraph.addEdge(edge1);
87            callgraph.addEdge(edge2);
88          END
89          ELSE // the element is already in callgraph
90          BEGIN
91            // retrieve condition as cond from callgraph
92            CGConditionVertex cond = callgraph.getVertex();
93            /*
94            Link the the first vertex
95            with the condition (cond) and condition
96            with the second vertex.
97            */
98            edge1 = new Edge(vertex1,cond);
99            edge2 = new Edge(cond,vertex2)
100           // add them to the callgraph
101           callgraph.addEdge(edge1);
102           callgraph.addEdge(edge2);
103         END
104       END
105       ELSE // there is more than one condition
106       BEGIN
107         prevCondition = vertex1;
108         FOR(every condition in conditions)
109         BEGIN
110           IF(condition IN callgraph)
111           BEGIN
112             // retrieve this vertex
113             cond = callGraph.getVertex(condition)
114           END
115           ELSE // we have to create a new vertex
116           BEGIN
117             // create a new vertex
118             cond = new CGConditionVertex(condition);
119           END
```

```
120           /*
121           create an edge between the condition and
122           prevCondition, and add it to the
123           callgraph
124           */
125           edge1 = new Edge(prevCondition,condition);
126           callgraph.addEdge(edge1);
127           /*
128           set prevCondition equal to condition
129           */
130           prevCondition = condition
131         END
132         /*
133         create the edge between condition and the
134         second vertex and add it to callgraph
135         */
136         lastEdge = new Edge(condition,vertex2);
137         callgraph.addEdge(lastEdge);
138       END
139     END
140   END
```

7.3.2 Class Hierarchy Graph Algorithm

Name
Class Hierarchy Graph Algorithm

Developed by
Holmen and Strand

File
code.Graph.ClassHierarchyGraph.CHGGraph

Purpose
When analysing several Java-files, or a file with several class declarations, it is no guarantee that an extended class already has been analysed. To avoid problems in the order of the declarations of the classes (see example 2), we had to make an algorithm that can handle such problems.

2 Example

The following code fragment might lead to problems

```
3  class A extends D {}       //D is not declared
4  class B extends C {}       //C is not declared
5  class C extends D {}       //D still not defined
6
7  //finally the definition of D
8  class D extends Object {}
```

The problem is that several classes inherit classes that have not been declared yet. In the case of A (line 3), this class cannot be added to the class hierarchy graph, because its super class D has not been declared yet. A has to wait until D is declared. Then D can be added to the class hierarchy graph, followed by A.

The class implementing the algorithm contains one fundamental member variable:

`scan_list`
: This is a vector containing classes that have been declared, but whose super class has not been declared yet.

In the first line of the code example above, D is not declared, but it is referred to in an extends-relationship. A is declared, but its super class is not. Therefore, A will be added to `scan_list`.

Prerequisites
Prerequisites for the algorithm are that we have a parse tree containing objects of type PTNode, and that these objects implement the createCHG method. During the parsing, all classes that extend Object are added to the class hierarchy graph directly. All other classes are added to `scan_list`. When starting this algorithm, we have some classes in the class hierarchy graph and some in the `scan_list`.

The Algorithm
The algorithm is implemented in the method `CHGGraph.emptyAll()`, and is outlined in the following.

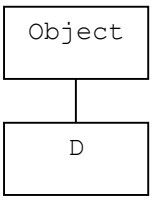
```
141  /*
142  As long as there are elements in the scan_list,
143  keep scanning through it.
144  */
145  WHILE(scan_list NOT empty)
146  BEGIN
147    FOR(every currentClass in scan_list)
148    BEGIN
149      /*
150      Get the class at the current position (i)
151      */
152      currentClass = scan_list.getElementAt(i);
153      /*
154      Fetch the name of the super class of currentClass
155      */
156      superClass_name = currentClass.getSuperClass();
157      /*
158      Get the super class of currentClass from the class
159      hierarchy graph, returns null if not found
160      */
161      superClass = findClassWithName(superClass_name);
162      /*
163      If the superClass is not in the scan_list and
164      not in the class hierarchy, then we know that
165      superClass must be imported, i.e. it belongs to an
166      imported Java-class. Create a new vertex in the
167      class hierarchy and set it's child
168      */
169      IF((superClass_name NOT in scan_list) AND
170        (superClass EQUALS null) )
171      BEGIN
172        /*
173        create a new node with the name of superClass
174        */
175        newNode = new CHGClassNode(superClass);
```

```
176         /*
177         Add the two new vertices to the graph
178         */
179         addVertex(currentClass);
180         addVertex(newNode);
181         /*
182         Add the two new edges
183         The first connects the root vertex and newNode
184         */
185         addEdge(chgRoot,newNode);
186         // The second connects the two new classes
187         addEdge(newNode,currentClass);
188         /*
189         We know that the new node must be imported,
190         since it wasn't in the scan_list and the
191         hierarchy
192         */
193         newNode.setImported(true);
194         /*
195         remove the current class from the scan_list
196         */
197         scan_list.removeNodeWithName(currentClass);
198       END
199       /*
200       the super class of the current class already exist
201       in the class hierarchy
202       */
203       ELSE IF(superClass NOT null)
204       BEGIN
205         /*
206         add the current class to the
207         class hierarchy
208         */
209         addVertex(currentClass);
210         /*
211         remove the current class from the scan_list
212         */
213         scan_list.removeNodeWithName(currentClass);
214       END
215       ELSE
216         /*
217         superClass of currentClass is in the scan_list,
218         we don't need to do anything, since superClass
219         will be added to the class hierarchy before we
220         reach the end of scan_list.
221         */
222         do nothing;
223     END
224 END
```

3 Example

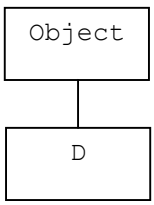
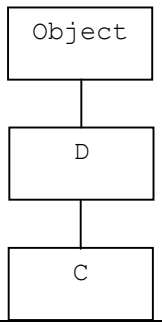
In this example we illustrate how emptyAll() works on the declarartions presented in example 2.

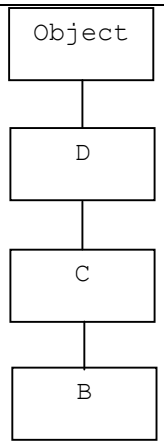
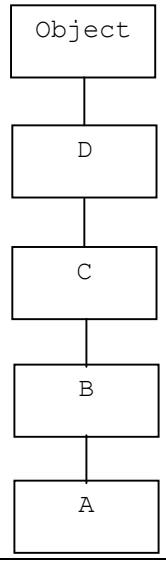
Class D, which extends Object, has already been added to the class hierarchy graph, which now consists of:



The other classes have been added to scan_list, which consists of:
scan_list(A, B, C)

Method emptyAll() is called, going through the scan_list as long as there are more elements in it.

Step	emptyAll()	scan_list after step	Class hierarchy graph
1	Get first element (A), and its super class (B). Check B: True at line 215 => do nothing.	scan_list(A,B,C)	
2	Get next element (B), and its super class (C). Check C: True at line 215 => do nothing.	scan_list(A,B,C)	Same as in 1
3	Get next element (C), and its super class (D). Check D: True at line 203 => add C to class hierarchy graph, remove C from scan_list.	scan_list(A,B)	
4	Get next element (A), and its super class (B). Check B: True at line 215 => do nothing	scan_list(A,B)	Same as in 3

5	Get next element (B), and its super class (C). Check C: True at line 203 => add B to class hierarchy graph, remove B from scan_list.	scan_list(A)	
6	Get next element (A), and its super class (B). Check B: True at line 203 => add A to class hierarchy graph, remove A from scan_list.	scan_list()	

7.3.3 Variables

Name
Variables

Developed by
Holmen and Strand

File
The algorithm is implemented in several files. UTILVariableStack.java contains the code that administrates the variables. This class is used by several classes in the package code.Parsing.

Purpose
The purpose of this algorithm is to find which variables that are valid at a point in the program. We must know these variables to find the correct object and parameter types in method calls.

Prerequisites
The class hierarchy graph generation must be finished.

The Algorithm

In order to create a correct call graph, we must know the type of the local variables in the program. The type is used when we match method calls and method declarations. A problem arises when a variable is declared within a block (for, while, if, else, try or catch). This variable will only be valid inside the block, and unknown to the rest of the program. When we decide the types of the variables used in method calls, we need to know where the variables were valid, see example 4.

4 Example

We have two different methods (line 13 and 14) called `calculate`, but one takes a float variable as parameter, while the other takes an int.

```
9  public class test
10 {
11   private int var1 = 0;
12
13   public void calculate(int var){}
14   public void calculate(float var){}
15
16   public test()
17   {
18     boolean finished = false;
19
20     while(finished == false)
21     {
22       float var1 = 0.0f;
23       finished = true;
24     }
25     calculate(var1);
26   }
27 }
```

In this case `var1` defined at line 11 is the one that is valid in the method call at line 25. The `var1` defined at line 22 is not known outside the while block. In other words, `calculate(int var)` is called.

We have used a stack to remedy this problem, defined in the class UTILVariableStack. We also defined a class CGLocalVariable, where the variable's name and type is stored. Every time we find a variable declaration, we add a CGLocalVariable-object to the stack. To know where the variables are valid, we add a unique identifier of type Integer every time we enter a block. When we leave a block, we delete all objects on the variable stack, including the unique identifier for that block. This way, we always know which variables are valid at any point in the program.

When we discover a method call, we check the parameters of the call. If any of the parameters is a variable, we search the variable stack for a variable with this name. We know that the first variable with the same name is the one we are looking for. However, if we cannot find the variable, we search through the member variables of this class. If we have not found in this class, we search up in the class hierarchy until we find it. When the variable is found, we get its type. In some cases, the variable may be defined in a class that is not analysed. Then we will not know the type, and we just write the name of the variable as its type.

7.3.4 Placing Text in the Vertices

Name
Placing Text in the Vertices

Developed by
Strand and Holmen

File
Code.Graph.Vertex

Purpose
Every vertex has a name. In the class hierarchy graph, the name is the name of the class. In the call graph each vertex has either the name of a method invocation, or a condition. The name must be placed within the vertex to allow the user to recognize the vertex. Due to the fact that many of the strings are wider than the 100 pixels of the vertex, we had to implement an algorithm for splitting long names into shorter ones. Inside a vertex there is room for four lines of text. In the following, we have outlined the algorithm that makes sure that the names fit inside the vertex. The method works for both the rectangular vertices and the condition vertices, which are hexagons.

Prerequisites
None

The Algorithm
The algorithm is implemented as a recursive method. This means that there are four possibilities every time the method is called. These possibilities and the according action is presented below:

1. We have already written three lines of text, and the remaining string is still wider than the vertex. In this case we print the first part of the remaining string, and replace the rest with three dots (…). The line counter is reset.
2. We have written three lines already, but the remaining string is smaller than the vertex. In this case we print the rest of the string and reset the line counter.
3. The string is smaller than the vertex. We write the complete string and reset the line counter.
4. The string is wider than the vertex. In this case, we have to try to split the string into several parts. It would be best to split after a dot (punctuation mark) or before an upper case letter. There are three alternative situations:
    i. The string has a dot within the width of the vertex and it is not among the first six characters. In this case, we split just after the dot. Call this method with the remainder of the string, after updating the line counter by one.
    ii. The string has an upper case letter within the width of the vertex and it is not among the first six characters. If so, we split just before the upper case letter, allowing the upper case to start a new line of its own. The line counter is updated and the remaining string is sent as parameter to the new call to this method.
    iii. The string does contain neither dots nor upper cases. We split the string so that the first part fits within the width of the vertex. After updating the line counter, we call this method with the rest of the string.

7.3.5 The Test Data Generation Algorithm

Name
Test Data Generation Algorithm

Developed by
Holmen and Strand

File
code.PackageInterfaces.GraphInterface

Purpose
To generate test data for the analysed system.

Prerequisites
A completed call graph with conditions.

The Algorithm
The algorithm performs the following operations:

1. Find all leaf vertices in the graph. These vertices are stored in a vector called bottom. Then, retrieve all the elements in bottom one by one. For each element in the vector, perform operation 2 and 3.

2. Find the parent of the vertex. There are two alternatives:
   A. If the parent is a CGConditionVertex, test data that satisfy this condition is generated. These test data are stored in a String variable.
   B. If the parent is a CGInvocationVertex, no data is generated.

   Every edge traversed by the algorithm is marked as visited.

3. The operation in 2 goes on until the parent is the main method of the system. When the main method is the parent, test data generation is stopped. The String containing the test data is presented to the user.

4. When all leaf vertices have been processed, the algorithm finds all the edges that have not been visited yet. These edges are stored in a vector called edgesNotVisited.

5. The vector is sorted. The intention behind this operation is to place those edges that are deepest in the graph at the front of the vector. Treating these edges first minimizes the likelihood of treating an edge more than once.

6. The routine in 2 is repeated for all members of edgesNotVisited. The edge is retrieved, and the algorithm finds the path connecting it to the main method. A test data set is generated for each vertex along the path. The algorithm stops when all elements in edgesNotVisited have been treated.

When generating data for an if-then-else vertex, one has to follow a special algorithm, which is outlined below.

Remember that test data generation always progresses upwards. When arriving at an if-then-else condition, one has to know the previous vertex the algorithm passed through. There are three different alternatives with corresponding actions:

1. The last condition was an if-condition. This corresponds to the rightmost branch in figure 10. In this case data has already been generated for the condition, and the algorithm does nothing.
2. The last condition was an else-if condition. This corresponds to the centre branch of figure 10. We then progress through the following steps:
    - Find all conditions that are before the else-if in question, and store them in the vector brothers. We organise the conditions in logical order. This means that the if-condition is first, followed by the else-if-condition(s). The else condition is logically at the end. In the figure below, only the if-condition is before the else-if. The else-condition is after the else-if.
    - Find the corresponding if-condition, and generate data so that this condition is false.
    - Ensure that the test data are false for all members of the vector brothers, and true for the current else-if condition. If one condition evaluates to true, new data are generated for the if-condition. This operation goes on until all conditions in brothers evaluate to false.

3. The last condition was an if-condition. In this case, we find all conditions that precede the else-condition, and store them in the vector brothers. This means that brothers contains all conditions in the if-then-else block, except the else condition. We find the if-condition, and generate data so that this condition is false. Afterwards we investigate if these test data falsify all other conditions in brothers. If one condition is true, we generate new data for the if-condition, and perform the investigation again. We stop this loop when all conditions in brothers evaluate to false.

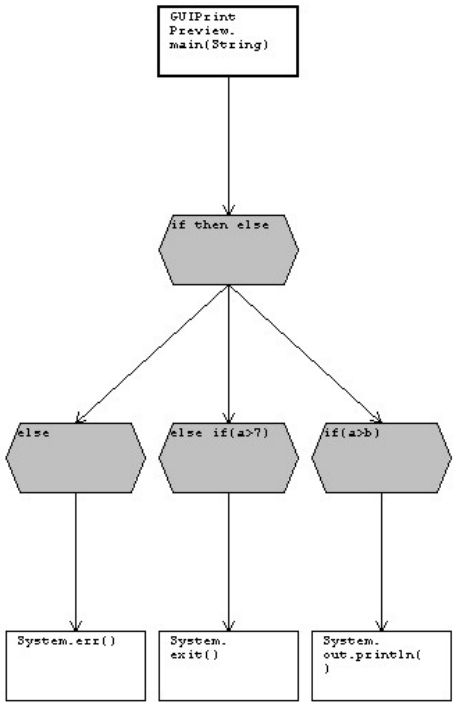


Figure 10: The annotated call graph for an if-then-else condition

8 ANNOTERT KALLGRAF 1.0

8.1 SYMBOLS USED BY ANNOTERT KALLGRAF

The symbols used in the graphs are based on the Extended Structure Diagrams (ESD) used by SINTEF [3]. ESD uses a combination of an octagon and a rectangle to symbolize a condition that has to be true for a method to be invoked. To reduce the complexity of the graphs we have replaced these two symbols with one hexagon containing the condition.

8.1.1 The Class Hierarchy Graph

In the class hierarchy graph, there is only one symbol used, in addition to the lines linking the vertices together. A simple rectangle with text symbolizes a class in the analysed program, see figure 11. The text is the name of the class. Long names are split in order to fit inside the rectangle (see section 7.3.4). If the text still does not fit after four splits, it is shortened (can be seen by the name ending with three dots). The top node in the class hierarchy graph will always be Object, since every Java class in some way or another extends Object. A problem arises when the analysed program contains a reference to a class that is not defined in the files. If a class extends a super class that Annotert Kallgraf does not find, the super class will be placed directly between Object and the analysed class.

Figure 11: A vertex in the class hierarchy graph

8.1.2 The Call Graph

The call graph has two symbols, a rectangle and a hexagon. Every called method in the analysed program is represented by a rectangle in the call graph, see figure 12. Inside the rectangle there is a text, at least two strings separated by dots. The String sequence contains the name of the class where the method is defined, and the name of the method that is invoked. As in the class hierarchy graph, the name may be shortened to fit inside the rectangle. The main method is recognized by thicker boundary lines.

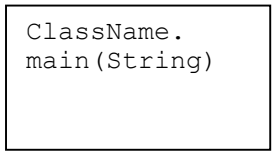


Figure 12: An invocation vertex in the call graph

The other symbol in the call graph, a hexagon, is the condition vertex (figure 13). In the analysed program, there will often be conditions that must be true for some methods to be invoked. Every time Annotert Kallgraf locates a method call that is dependent on a condition, a condition vertex is drawn between the caller and the callee.

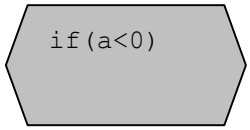


Figure 13: A condition vertex in the call graph

The "regular" condition vertex contains a condition, e.g. for or if. However, a problem arose when trying to visualise many if-then-else statements. From the visualization it was impossible to understand which if-vertex that corresponded to the else-vertices. We decided to create a special condition vertex that contained the text "if then else", se figure 14. For every if-then-else statement in the code, this type of vertex is created. Below it in the call graph, the if and else conditions that belong together is located (see also Example 1, figure 15, in section 8.3.1)

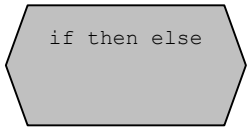


Figure 14: The special if-then-else condition vertex

8.2 SYSTEM FUNCTIONALITY

In this section the most important features of Annotert Kallgraf are described. For more details about how to use the system, please see the user manual.

8.2.1 New Analysis

To start a new analysis is the most basic operation in Annotert Kallgraf. Most functionality will not be enabled before an analysis is performed. When the user wants to start a new analysis, a dialog box will pop up. Here the user can select the file(s), directory (-ies) or files and directories that are to be analysed. After selecting the files, another dialog box will be shown. Here, the system provides feedback to the user about the current progress of the analysis.

When the analysis is completed, two graphs are drawn in the right part of the graphical user interface (GUI). One graph shows the class hierarchy graph of the analysed program, while the other is the call graph. In the left part of the GUI, the class hierarchy tree is presented. The tree contains all the classes in the analysed program, and every member method and member variable is presented as a leaf node in the tree.

8.2.2 Save Open Analysis

The user has the possibility to save an open analysis. The graphs and the trees are saved. The saving action will open a new dialog box, where the user can name the file where the analysis is to be saved. All saved analysis will be saved as files with the extension *.aks*.

8.2.3 Open Saved Analysis

It is possible to restore a saved analysis. A dialog allows the user to locate a previously saved *.aks* file. A restored analysis will behave as a recently generated analysis. The system will not allow the user to open a new analysis, if another analysis is currently open.

8.2.4 Close Analysis

The user can easily close an open analysis. If the user closes an analysis, all information about this analysis will be lost. Thus, it is important that the user saves the analysis before closing, if (s)he wants to keep it. However, in most cases it is quite simple to regenerate the analysis by selecting the same files in a new analysis.

In order to start a new analysis or open a previously saved file, any currently open analysis must be closed.

8.2.5 Print Preview

Before printing a graph, the pages can be previewed. The print preview will show the graphs exactly as they will be printed on paper. The user can choose to only preview a part of the graph, by marking a part of the graph (see the Print section for details). The preview will be drawn with the current zoom factor (see 8.2.7 for details on zooming). In preview mode, the user can select the zoom factor of the previewed pages, and a smaller value will show more pages at the same time. Note that this zoom factor has nothing to do with the zoom factor in the main application.

8.2.6 Print

The print functionality allows the user to print the graphs on any printer already installed on the computer. A dialog box will pop up, and the user can specify which pages that are to be printed, the number of copies etc. The graphs will be printed in landscape orientation as default. Printing with a zoom factor of 100% will give large and few vertices on every page, while a zoom factor of 50% will give a readable text.

The user can choose to print only a selected part of the graph. Clicking and dragging in the graph window will select the area. A red rectangle shows the selection. Nothing outside the rectangle will be printed. It is fully possible to select an area larger than the screen, either by using the zoom functionality or by moving towards the edge of the window while selecting (which will result in auto scrolling of the window).

Only the graph in the active window will be printed.

8.2.7 Zooming

The user can zoom in and out on the graph. At start-up, the zoom factor is 100%, but the user can change it at any time. The only requirement is that the graph windows are open. The zoom functionality can be used to get an overview of a bigger part of the graph. If the user selects an area while zoomed, the same area of the graph will be selected when zooming out. In other words, a part of the graph can be chosen with a zoom factor of 10% and the same part will still be selected at a zoom factor of 50%.

8.2.8 Generating Test Data

To generate test data, the user is presented with a dialog box. In this dialog box one can choose the class for which the test data will be generated. After choosing the class, the generated test data is presented in another dialog box. Here the user can save the data to a regular text file.

8.2.9 Copy Graph to System Clipboard

The graphs can be copied to the system's clipboard for use in other application, e.g. in Microsoft Word. The graphs are copied as jpeg images, and can be pasted into any application that handles images. The active graph is copied either via the menu or ctrl-c.

If a part of the graph is selected (see 8.2.6 Print for details), only the marked part of the graph will be copied to the clipboard. This functionality has only been tested in Microsoft Windows.

8.2.10 Save a Graph as an Image

The graphs can be saved to disk as jpeg-images. The currently active graph will be saved to the user specified location.

8.2.11 Show Standard Java Methods and Classes

A standard Java method is a method that is not defined in the analysed files. Likewise a standard Java class is a class that is defined outside the parsed files. The user can select whether or not the standard Java methods and classes should be shown in the graphs. If the user does not want to see the standard Java classes, the classes that are not defined in the analysed files will not be drawn in the class hierarchy graph. The same goes for the call graph and standard Java methods.

8.2.12 Arrange Windows

The two graph windows in the right part of the GUI can be arranged automatically. The user can select to either cascade the windows, or tile them horizontally.

8.2.13 Help Functionality

Annotert Kallgraf has built-in help functionality. The help files are presented in a new window. The help files are in most respects the same as the user manual. The files are html files and can be navigated through links.

8.3 EXAMPLES

8.3.1 Call Graph Example 1

The following code fragment will result in the call graph presented in figure 15.

5 Example

```
28 public class write
29 {
30   public static void main(String args[])
31   {
32     int a=0;
33     float b = 0.0f;
34     if(a>b)
35       System.out.println();
36     else
37       foo();
```

```
38   }
39
40   public void foo()
41   {
42      write();
43   }
44 }
```

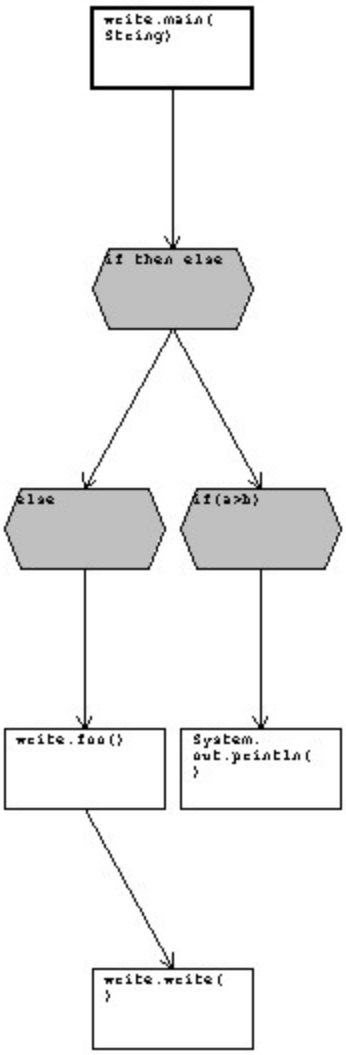


Figure 15: The call graph for the code in example 5

8.3.2 Call Graph Example 2

The all graph in figure 16 is generated for the combined code of the following files (all located in the code.Visualization.GUI-package):

- GUIDialog.java
- GUITestDataDialog.java
- GUIProgressDialog.java
- GUIClassListDialog.java

- GUIAboutDialog.java

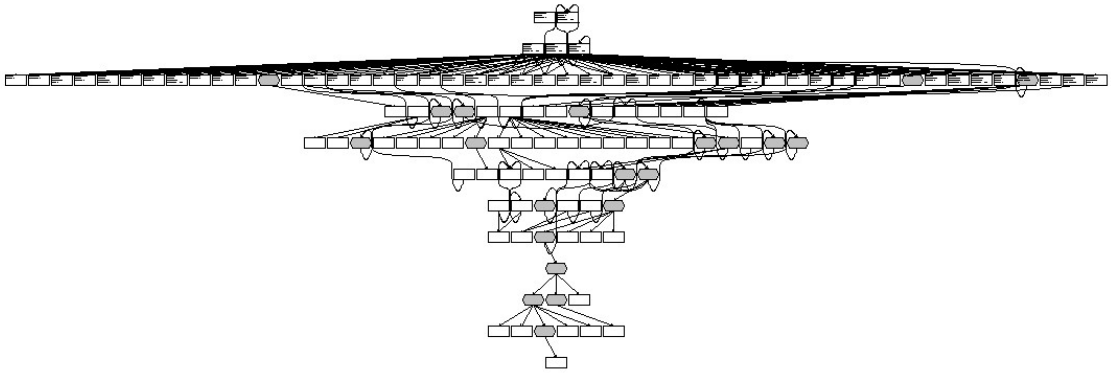


Figure 16: The call graph for GUIDialog and its sub-classes

9 TESTING

In this chapter, we discuss different types of testing and their relations to the call graph. In section 9.5 we describe how our system is related to testing.

9.1 BLACK BOX TESTING

In this type of testing, the system is seen as a black box. This means that no information about the internal system structure is available, only the inputs and the outputs of the program. The system is seen as a black box that is receiving inputs and generating outputs.

Black box testing is only weakly related to the annotated call graph. In order to generate the call graph, one needs access to the code of the system. This is not necessary when performing black box testing. In addition, the call graph gives information about the internal structure of each method. Therefore, the graph contains much more information than is actually needed to do black box testing of a method. Thus, it is not useful to connect black box testing and the call graph.

9.2 WHITE BOX TESTING

In white box testing, the internal structure of the code is analysed to generate test data. The advantage of this kind of testing is that a code analysis can be used to find the path coverage. A path is a sequence of edges that connects the main method to a leaf vertex. A leaf vertex is a vertex that has no outgoing edges. In Annotert Kallgraf, all the standard Java methods (see section 8.2.11) are leaf vertices.

9.2.1 Path testing

This is a kind of testing where the objective is to test every path through the program. The system is represented as a flow graph. Every program statement is represented in this flow graph. Special vertices represent if-then, if-then-else and while-statements. The flow graph resembles the annotated call graph that we have generated. However, the flow graph contains every statement in the program, whereas the call graph only represents method calls. This means that the two graphs are a bit different; see example 6.

6 Example

The following code fragment, written in Java, will be represented differently in a flow graph and an annotated call graph:

```
45 while(I < 100)
46 {
47   Number++;
48 }
```

The statement inside the block is an increment statement. Therefore, it will be represented only in the flow graph. The annotated call graph will ignore this block because it does not contain any method invocations.

The test path coverage is a fraction. It represents the number of paths that are executed by a test data set, divided by the total number of paths in the graph. From the tester's point of

view it is important to maximize the test path coverage, because this ensures that a high number of program paths have been executed. However, for everything but simple programs, it is impossible to achieve test coverage of 100% for a single test data set, as illustrated by example 7.

7 Example

An if-then-else statement makes it impossible to achieve a test coverage value of 100%:

```
49 if( A > B)
50 {
51 }
52 else
53 {
54 }
```

Any test data set that satisfies the condition A > B, will follow the first path but not the second. Any data set satisfying the else condition (i.e. A ≤ B) will follow only the second path, but not the first. This means that in the presence of if-then-else statements, test path coverage of 100% is impossible. In practice, the solution is to generate several test data sets that altogether guarantee that every path will be followed. As testing is a tedious activity, it is still important to find a test data set that maximizes the test coverage.

Two other problems arise when generating test data:

- Even when test coverage of 100% has been achieved, this does not mean that the system has been thoroughly tested. It only means that all paths have been followed in the execution of the program.
- It is impossible to generate test data for all *combinations* of paths. It is possible to generate test data that follows one path after another. However, the number of combinations of paths is enormous for all but trivial programs.

In spite of these two problems, we believe that it is natural to use white box testing when generating test data from an annotated call graph. We have used this approach in our tool.

9.3 INTERFACE TESTING

Interface testing implies testing the interaction between different components. This type of testing is used when integrating different components of a program. Each component has a defined interface that is used by other components. The objective of interface testing is to detect faults that may have been introduced because of errors in the interfaces. Testing a single unit cannot expose most interface errors, because they are the result of the interaction between components.

Interface testing focuses on the practical consequences of actually running the program. A static call graph generator does not execute a program; it just visualizes its structure. It does not show which invocations that are done during execution. Interface testing requires the execution of the program. Since our system is a static call graph generator, it is difficult to generate test data based on the conditions that are stored inside a method. On the other hand, it is possible for a static call graph generator to generate a test program. This

program might instantiate objects of different classes, and invoke their interface methods. In this case, the program would generate a Java source file containing test code. This file might be compiled and executed by the user.

9.4 UNIT TESTING

Unit testing is performed by invoking the different methods of a program unit, for example a class. The disadvantage of unit testing is that it only tests the interface of the class as a single component. Errors stemming from the interaction with other components would not be exposed.

Unit testing requires the practical execution of a program. For a static call graph generator, this is impossible. What is possible, though, is to generate a program that creates a class object and calls its methods. However, generating this program is nontrivial, because there are usually dependencies between classes. Calling one object's methods might require the instantiation of several other objects because of dependencies between classes. Detecting these dependencies is a difficult task.

9.5 USE OF ANNOTERT KALLGRAF IN TESTING

Annotert Kallgraf has a simple and rudimentary test data generator. The approach is based on white box testing. The generator evaluates every condition in the graph, and generates a test data set that satisfies this condition. For every data set, the test coverage is also calculated. However, this calculation is not based on the different paths (see path testing, section 9.2.1) of the program. Instead, it is based on the edges of the annotated call graph. The edges of the graph are of two types:

- Trivial edges, for example those connecting two conditions.
- Non-trivial edges connecting a condition and a method invocation.

For every data set, Annotert Kallgraf calculates the number of non-trivial edges that are passed by using the data set. In addition, the total number of non-trivial edges in the graph is calculated. The test data coverage is the division of the two numbers.

The test data generator has several weaknesses:

- It only generates test data for numeric (float, double and integer) data types.
- If there are non-numeric data types inside a condition, test data is not generated.
- If there is a method call inside the condition, test data is not generated. Similarly, it does not generate data for conditions that contain inequality (!=), equality (==) or division (/).
- Test data is generated individually for each condition. If there are dependencies between conditions (for example if the same variable is appearing in two conditions), the generator does nothing to detect these dependencies. On the other hand, exploiting such dependencies requires knowledge about all operations that are performed on a variable.
- When data has been generated, the programmer must manually manipulate the code by filling in the values of the variables. Afterwards, the program must be compiled and executed.

10 THE SYSTEM'S USE IN RELIABILITY AND SAFETY

10.1 RELIABILITY

Reliability is defined as conformance to a specification [5]. The word specification is subject to interpretation, but it may be a requirements specification written in a natural language, for example English. The problem is that there is a large difference between a requirements specification and a call graph. The specification is usually written in a natural language, whereas the call graph displays constructs in a programming language. The large difference between the two makes it difficult to see how the call graph might play a role in assessing the reliability.

However, there are other definitions of reliability. Sommerville [6] defines the reliability of a system as "a function of the number of failures experienced by a particular user of that software". A failure is defined as "a situation in which the software does not deliver the service expected by the user". A software failure is caused by a software fault, which may be a programming or design error. Thus, programming faults might result in software failures, which in turn affect the reliability of the system. The annotated call graph makes it easier to detect software faults, because it displays the structure of a program. It visualizes method calls and their conditions, making it easier to see which conditions the system is not programmed to tolerate.

8 Example

```
55 if(var > 13)
56 {
57     method_call();
58 }
```

In example 8, the system does not take any action in the case where `var` is less than or equal to 13. If `var` equals 0, the system will not take any action. Maybe a software fault is introduced if `var` has a value less than or equal to 13. One does not need a call graph to see that the system only takes action if `var` is greater than 13. A program inspection can verify this. However, program inspections are tedious. It is easier to spot potential errors if the program structure is visualized. The annotated call graph visualizes this relationship, and it may therefore be helpful in improving the reliability.

There are several different metrics that are used to assess the reliability of a system. One well-known metric is the complexity coefficient of Henry and Kafura [6]. This coefficient calculates the complexity of a single component, and the coefficient is based on the following equation:

$$\text{Complexity} = \text{length} \times (\text{fan-in} \times \text{fan-out})^2$$

All the variables of the equation are component-level variables. The length is a measure of the length of the component, e.g. its length in lines of code or McCabes cyclomatic complexity (see Glossary, page 50). The fan-in is the number of edges that are incoming to the component, see figure 17. The fan-out is the number of edges that leave the component. In call graph terminology, the component is the method. The fan-in is the number of methods that call the method in question, while the fan-out is the number of

methods that are called from that method. In our call graph-generating tool, standard Java methods would always have a coefficient value of 0, because their fan-out value is 0.

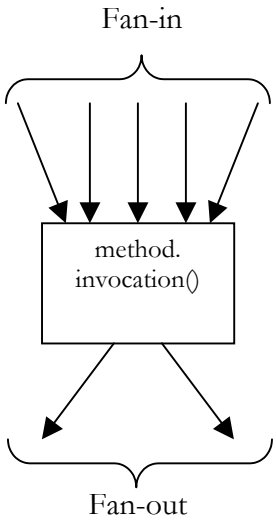


Figure 17: Fan-in and fan-out

The objective of Henry and Kafura was to identify the components that are likely to produce errors, and thus affect the reliability. The two researchers validated their metric on the Unix operating system. The results showed high values of this metric for components that had caused a disproportionate number of system problems [6].

The importance of the call graph is that it displays the edges that are the basis of the fan-in and fan-out calculations. Fan-in is the number of incoming edges, whereas fan-out is the number of outgoing edges, numbers that can easily be calculated from the call graph. By supplying a value for the length variable of every method, the complexity coefficient can be calculated for every method in the call graph. Thus, the system could sort the methods based on the values of their coefficient. This would enable the system to locate the methods that require special attention from developers.

Cheung has introduced another reliability metric [7]. Cheung's metric reflects the reliability of the whole system as a probability of its successful execution. The metric is based on the following variables:

- Every component in the system has a reliability value that reflects the probability of a successful execution of this component. If this value is 0.985, the likelihood of error when executing this component is 0.015, or 1.5 %.
- The system has a set of transitions. A transition is a branching from one component to another. In call graph methodology, a transition is a method call. When method A calls method B, control is passed from A to B. Thus, the transfer of control from A to B is a transition.
- Every transition has a probability of occurring. These probabilities are gathered in a matrix. The matrix entry [i,j] is the likelihood of method i calling method j.
- Every component corresponds to a state in the system. If the system is inside component K, then it is said to be in state K. This means that every method in the call graph corresponds to a state.
- Two additional states are introduced. These are the states C (correct) and F (failure). C occurs if the results of the system are correct. The system ends in state

F if an error occurs during execution. Because a run of the system is either a success or a failure, it has to end up in one of these states.

According to Cheung's metric, the system reliability is the probability of starting from an initial state and ending in state C (where the system has produced correct output). The calculation is based on two sets of data:

- The reliabilities of the individual components
- The probabilities of transition from one state to another.

The annotated call graph might be of importance when calculating the transitional probabilities. Usually, these probabilities are difficult to calculate, and it is tempting to use a uniform probability distribution when generating these values. However, the annotated call graph displays the conditions that have to be fulfilled before a transition is performed. Based on these conditions, it is possible to calculate realistic probabilities for the transitions. This means that the final value of the reliability metric might be more realistic.

We conclude that the annotated call graph might simplify the calculation of some well-known reliability metrics. However, these calculations are not implemented in our system at present.

10.2 SAFETY

Safety is defined as "freedom from those conditions that can cause death, injury, occupational illness, damage to (or loss of) equipment (or property), or environmental harm" [5]. Thus, safety is a function of the relationship between the system and its environment, as shown in figure 18.

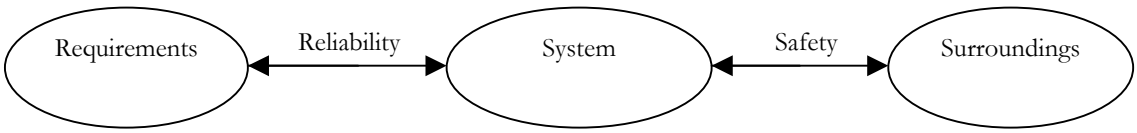


Figure 18: The relationship between the system, reliability and safety

The safety risks of a system are usually illustrated by using a fault tree (see example 9). A fault tree is a logical diagram illustrating the connection between an unwanted event in a system and the reason for this event [8]. The fault tree is conceptually close to the system's environment, because it is constructed based on the errors that might occur when the system is executing.

The call graph, on the other hand, is constructed from the source code of the system. It does not say anything about the system's environment. It is impossible to define the environment by looking at the call graph. This means that there is a gap between the fault tree and the call graph.

However, annotated call graphs and fault trees may be combined to help doing safety analysis and safety validation. A safety testing approach that makes use of both fault trees and annotated call graphs is described in [3]. The approach has six steps:

1. Specify the system's environment and architectural design
2. Perform a HazOp-analysis, which results in a set of safety risks. These risks are called hazards.

3. Analyse all identified hazards by using fault tree analyses. The fault tree analysis determines the possible reasons for every failure.
4. Perform white box testing. This step is optional. If white box testing is performed, steps two and three have to be repeated for the implemented system.
5. Use the fault trees to identify safety related failure modes
6. Develop tests and checklists for every hazard.

In step four, Extended Structure Diagrams (ESDs) are used to increase the knowledge and understanding of the analysed system. The ESD will show in what state the software has to be in order to invoke a method call. The ESD is an annotated call graph, because it displays the conditions that have to be fulfilled in order for a method to be invoked. The diagrams used in [3] also use a syntax that is similar to the one in Annotert Kallgraf. The fault trees will show failures that are connected to certain methods or software components. By combining the fault trees and the annotated call graph, one gets a better understanding of how the software might affect safety.

9 Example

In this example, we want the system to shut down when the temperature exceeds a pre-defined value, or when the user manually tries to turn it off.

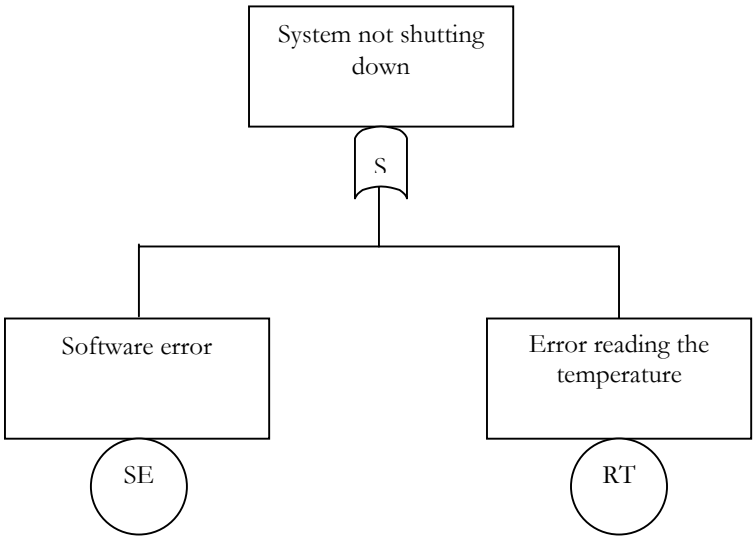


Figure 19: The fault tree for the given example

From the fault tree in figure 19, we see that there are two possible reasons why the system does not shut down when it is supposed to. Either the software is not acting correctly, or there is an error reading the temperature. In this example, we assume that the temperature reading only fails due to hardware problems, and disregard it for now.

By using the fault tree, we have located one source of potential hazard: The software fails. We know that the method shutdown() is responsible for shutting the system down.

By combining the information in the fault tree and the annotated call graph, it is possible to map the causes to the system states. This means that one identifies the method(s) that are called when the system is in a failure mode. In the example above, there is one failure

mode: "System not shutting down". This failure mode has two potential causes: "Error reading the temperature" and "Software error". Only the latter is connected to the software. The "Software error" cause is activated in the method shutdown, which is displayed in the annotated call graph. By combining information in the two diagrams, it is possible to identify the parts of the software that may cause safety risks.

When using only the fault tree, it is common to include the conditions of method calls in the diagram. However, when applying both fault trees and annotated call graphs, one should avoid multiplying the information that is stored in them. The annotated call graph stores information about the method calls and their conditions. Such information should be removed from the fault tree, thus making the latter more compact and readable. In addition, the fault tree is constructed for every failure mode. The annotated call graph, on the other hand, is constructed only once. This means that moving information from the fault tree to the call graph might save time in the safety analysis.

11 FURTHER WORK

11.1 EXTENSION TO C/C++

There is at least one important reason to extend Annotert Kallgraf to accept C and C++ code. Still, little safety critical code is written in Java, while much is written in C or C++. This was, however, not very important for us, since we have focused on the use of annotated call graphs in testing, and not so much its use in safety analysis.

11.1.1 The C Programming Language

C is not object-oriented. The programmer can declare data types by using the keyword `struct`. However, these constructs do not allow the use of inheritance. In addition, the use of `struct` is not mandatory. The programmer may choose not to use these constructs, and it will still be a syntactically correct C program. This has the following consequences:

- If the program does not contain any data types, there is no need for a class hierarchy graph.
- If the program does contain the declaration of data types, the structure of the class hierarchy graph is changed. The class hierarchy graph can only show the data types, but not the inheritance relations between them, as inheritance is not allowed.

11.1.2 The C++ Programming Language

C++ is object-oriented, and resembles Java. The main difference is that C++ allows multiple inheritance. In addition, C++ is not as strictly object-oriented as Java. In Java, any function must be declared inside a class, whereas in C++ a function might be declared without being connected to a class. This has the following consequences:

- The class hierarchy graph must be a graph, and not a tree, as in the case of Java. In Java, the class hierarchy graph is a tree, because any class can only have one parent.
- In some cases, no object is connected to a method invocation. In Java, this is mandatory.

11.1.3 Changes Needed for Extension to C/C++

In order to extend the system to allow analysis of C/C++ - files, the following changes must be made:

- A new parser must be generated for each of the new languages. This can be done by using the parser generating tools JLex [10] and Java CUP [11]. In addition, the algorithm that generates the call graph (implemented in GraphInterface.java) must be changed. This algorithm must check the types of files that are to be parsed, and use the appropriate parser. If the files are C++ source code files, then the algorithm must choose the C++ parser, etc.
- The algorithm that generates the call graph (implemented in GraphInterface.java) must be changed. The current implementation requires an object-oriented language. The class that stores information about the method declarations (Graph/CallGraph/CGMethodDeclaration), has a field called `classname`. In C/C++, this field might have the value null.

11.2 EXTENSION TO TEST PATH COVERAGE

In order to implement this, it is necessary to change the calculation of the test coverage. In the current implementation, this calculation only counts the number of relevant edges in the graph. Instead, one has to calculate the number of paths that are followed by exposing the system to a certain set of test data. However, some parts of the algorithm described in section 7.3.5 can still suffice. We believe that it is essential to find the leaf vertices of the graph, because any path has to end in a leaf vertex. In our implementation, we find one path connecting a leaf vertex and the main method. However, several different paths might connect a leaf vertex and the main method. A test path coverage algorithm has to consider all such paths, and not only one. In addition, the algorithm has to stop when all such paths have been traversed. Our algorithm now stops when all edges have been traversed at least once.

11.3 OTHER EXTENSIONS

11.3.1 Expanding and Collapsing Vertices

A problem with call graphs in general is complexity. For any system of some size, the call graph will be more confusing than informative. By introducing conditions into the call graph, the complexity has increased further. In [1], some usability considerations for call graph generation tools are presented. One of the considerations is "[…] to provide expanding or collapsing, subtree focusing or hiding, for the users to control the complexity of the focused information."

In Annotert Kallgraf 1.0, no such functionality is implemented. This is also the largest weakness of the application, since positioning and drawing the complete call graph of a relatively large program is time consuming. By introducing the possibility to expand or collapse vertices, this can be remedied. One might for example only display the number of vertices that is necessary to fill the drawing surface. The user selects which invocations to investigate further by clicking on a vertex to expand it and reveal further invocations.

11.3.2 Rapid Type Analysis

When finding the object types in the call graph, there are three approaches. We illustrate the differences between these three approaches with example 10.

10 Example

The program has the following class structure:

```
59 class SuperClass extends Object
60 {
61   public void draw() {}
62 }
63 class SubClass extends SuperClass{}
```

The main method is implemented as follows:

```
64 public static void main()
65 {
66   SubClass sub = new SubClass();
67   sub.draw();
68 }
```

These are the different approaches:

1. The naive approach. This means replacing the name of the object with its type, without checking whether the type is implementing the method. In the example above, this would mean replacing `sub` with its type (`SubClass`) in the method invocation draw. The problem is that `SubClass` does not have an implementation of the method draw. Therefore, using this approach introduces errors in the call graph.
2. The class hierarchy graph analysis approach. In practice, this means searching in the class hierarchy graph until one finds a superclass that implements the method. In the example above, one would replace `SubClass` with `SuperClass`, because this is the class that implements the `draw` method.
3. Rapid Type Analysis [13]. This is a type of analysis that removes certain edges from the call graph by considering the set of instantiated types. If a type is never instantiated, the methods from this type will not be called. RTA is an extension to class hierarchy graph analysis, and it requires the class hierarchy graph in order to work.

11.3.3 Reliability

The system can be extended to automatically generate the reliability measures described in section 10.1. However, this is a rather simple task. When calculating the Henry and Kafura coefficient, one problem is to supply a length measure for every method. This measure can either be calculated by the system or supplied by the user. In case of the Cheung coefficient, the problem lies in supplying the reliability values for each method. The user might provide these values to the system.

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14 GLOSSARY

Class hierarchy tree
The class tree is found in the left split pane and contains all the classes in the analysed files. Every class has its own node in the tree and two children. The first child contains a list of the member variables in the class. The second contains a list of all member methods.

Cyclomatic Complexity
The cyclomatic complexity [6], CC, of any flow graph G may be computed according to the following formula:

$$CC(G) = Number(edges) - Number(vertices) + 1$$

The term was introduced by McCabe in 1976 and is used to discover the number of independent paths in a program by the use of the flow graph.

HazOp
HazOp is short for Hazard and Operability analysis [8]. It is way of formally identifying potential safety risks that might occur during the execution of a technical system. The HazOp process is performed by a group of people, who investigate the system in a series of meetings. The output of the HazOp process is a table displaying the different safety risks and their consequences.

Look and feel
Look and feel is the visual appearance of an application. When developing Java applications you can choose which look and feel to use. If you choose the system's look and feel, the same application will change visual appearance according to which platform it runs on. In Windows it will look like other standard Windows applications, but in Unix it will look like other Unix applications. Java also has its own look and feel, which will remain the same on all operating systems.

Scroll bars
If an object is too big to fit in a window, scroll bars are implemented to allow the user to access the complete object. Both graphs and the class hierarchy tree are placed within scroll bars, which automatically will be shown when needed.

Split pane
The main window of the application is split in half by a horizontal bar. To the left of this bar, in the left split pane, the class tree is found. In the right split pane the call- and class hierarchy graphs are found (see figure 20).

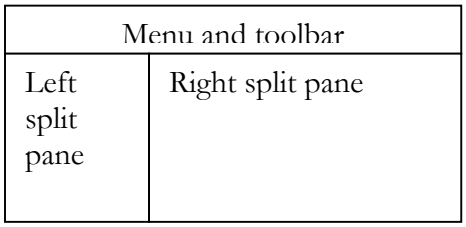

Figure 20: The layout of the application showing the splitpane

15 APPENDIX A

15.1 SYSTEM TEST ACCORDING TO TEST PLAN

During the work on the requirements specification for Annotert Kallgraf, we developed a test plan. The test plan was designed to test all the functional requirements of the finished system. In this chapter we present the test and the results.

15.1.1 The Test Plan

Introduction

In this section we describe how the system can be tested in compliance with the requirements stated in the requirements specification, section 5.

Functional Testing

T-F-1 Give a Java file as input and evaluate the result presented by the system
T-F-2 Give more than one file as input and evaluate the results
T-F-3 Ask the system for test data for a Java program, and check manually if the presented results are correct
T-F-4 Calculate the test coverage thoroughness manually with the given test data, and compare this to the results presented by the system
T-F-5 Give a Java program with conditional method calls as input to the system, and check the results manually
T-F-6 Give a Java program with calls to standard Java methods as input to the system, and evaluate the results
T-F-7 Turn the "see standard Java methods"-function in the system on and off
T-F-8 Check the system's feedback when it is working
T-F-9 Evaluate whether the system has a graphical user interface
T-F-10 Try to zoom in on a call graph
T-F-11 Try to zoom out on a call graph
T-F-12 Try to give the system a non-java file as input, and evaluate the results
T-F-13 Ask the system to present a Class Hierarchy Graph
T-F-14 Check manually if the name of the class the method is called for is presented and correct
T-F-15 Give a Java-file with several calls to the same method as input. Check if every method only is presented once in the call graph
T-F-16 Try to navigate horizontally in the call graph
T-F-17 Try to navigate vertically in the call graph
T-F-18 Give a program with a method that calls the same method several times as input, and check if the calls are only presented once in the call graph
T-F-19 Try to select one part of the graph and print it, and check if the printed graph reflects the chosen part of the call graph
T-F-20 Print a call graph that does not fit on a single page and evaluate the results
T-F-21 Evaluate if the system has a Windows based user interface

15.1.2 System Test

In the following test we used a small Java program. The program is given in example 11, and consists of two different files, Main.java and AnotherClass.java.

11 Example

Main.java

```
69 public class Main extends Object
70 {
71   public static void main(String args[])
72   {
73     AnotherClass ac = new AnotherClass();
74     int i = 1;
75
76     if(i > 0)
77       System.exit(0);
78     else
79       ac.exit();
80   }
81 }
```

AnotherClass.java

```
82 public class AnotherClass
83 {
84   public AnotherClass()
85   {
86     System.out.println("Opprettet klasse");
87     System.out.println("Konstruktør ferdig");
88   }
89
90   public void exit()
91   {
92     System.exit(0);
93   }
94
95   public void count(int i)
96   {
97     i++;
98   }
99 }
```

ST-F-1 When given a Java-file as input, the system generates a call graph and a class hierarchy graph. Methods that are not invoked are drawn as vertices without edges. AnotherClass.java resulted in the call graph shown in figure 21.

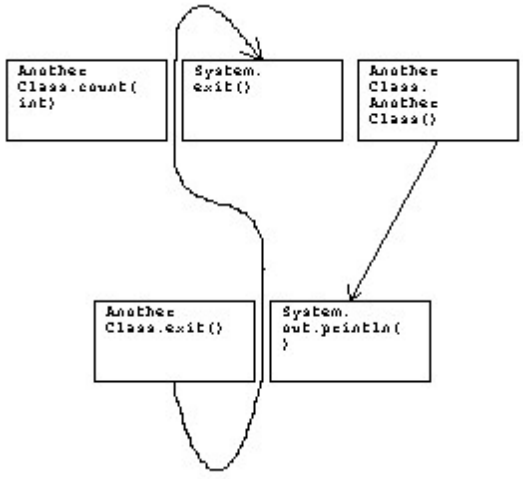

Figure 21: Call graph for AnotherClass.java

ST-F-2 The system generates one call graph and one class hierarchy graph for all the files. Methods that are not invoked are drawn as vertices without edges. The call graph for both the files in Example 11 is shown in figure 22.

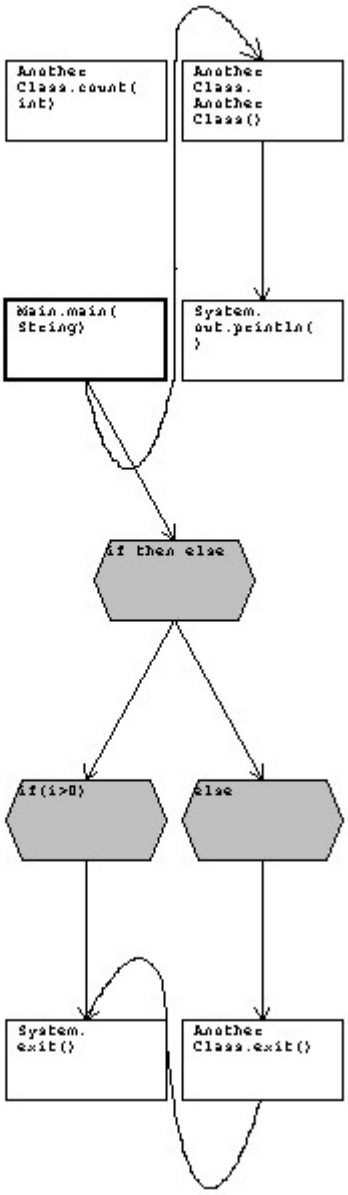

Figure 22: The call graph for AnotherClass.java and Main.java

ST-F-3 The system can generate test data for simple code. The generated test data for Main.java is shown below:

```
Forslag til testdata for Main
-----------------------------
Betingelse: else(i<0)
i =  -1
Dekningsgrad: 33.0 %
```

```
Betingelse: if(i>0)
i =  42
Dekningsgrad: 33.0 %
```

We see that the generated test data are correct for the example. The test data generator cannot handle complex cases, e.g. method-calls within conditions.

ST-F-4 The test code coverage for AnotherClass.java must be 66% since the constructor always is invoked, and either the second or the third method invocation will take place. As we can see from the previous example, the calculated test code coverage was not correct. However, if we remove the constructor invocation, the generated test code coverage is calculated to be 50%, which is correct.

ST-F-5 The system shows the conditions for method call inside a grey-coloured hexagon, as shown in figure 22. If-then-else constructions have their own vertex and all the parts of the construct is shown below in the graph.

ST-F-6 The system is able to tell standard Java-methods from other methods (see ST-F-7), but they are not visually different from the defined methods.

ST-F-7 There are two standard Java-methods in the example with both classes (figure 22). By de-selecting "Vis standard Javametoder" on the "Verktøy"-menu, they both disappear from the call graph, but the defined methods remain visible, as shown in figure 23.

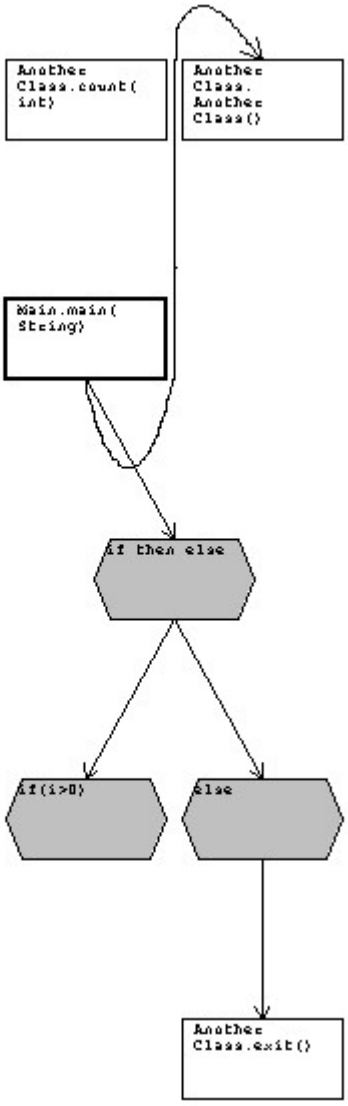

Figure 23: Call graph for AnotherClass.java and Main.java without standard Java-methods

ST-F-8 When a new analysis is started, two progress bars, showing the progress of the analysis, are presented to the user, see figure 24.

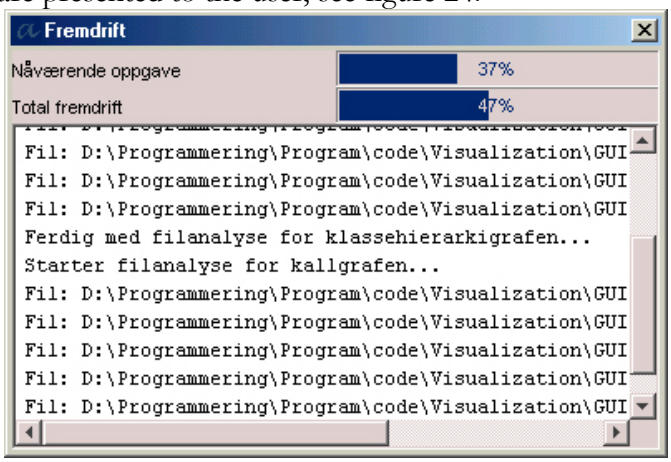

Figure 24: The progress dialogs shows information about the current state of the application

ST-F-9 The system has a graphical user interface

ST-F-10 By clicking on the zoom-in icon or selecting "zoom inn" on the "Verktøy"-menu, the graphs are enlarged.

ST-F-11 By clicking on the zoom-out icon or selecting "zoom ut" on the "Verktøy"-menu, the graph size is reduced.

ST-F-12 When trying to analyse a .txt-file, the system generated the following message in a message box: "Ingen Java-filer valgt".

ST-F-13 The class hierarchy graph of the analysed files is presented by default; there is no need for the user to ask the system to present it.

ST-F-14 The system presents the name of the class the method is called on behalf of. In the example presented above, AnotherClass`.exit()` is displayed in the graph, and not `ac.exit()` which is written in the code.

ST-F-15 From the code in example 11, we see that there are two calls to `System.out.println()`, but there is only one such vertex in the graph (figure 23).

ST-F-16 It is possible to scroll horizontally in the graph, if the graph is too wide for the window.

ST-F-17 It is possible to scroll vertically in the graph, if the graph is too high for the window.

ST-F-18 There are two calls to `System.out.println()` in the test example, but only one edge showing the call.

ST-F-19 We marked a part of the graph, and chose to print it. The printout showed exactly the area we marked. We also saved the graph as a jpeg-image with parts of it selected and the result is shown in figure 25.

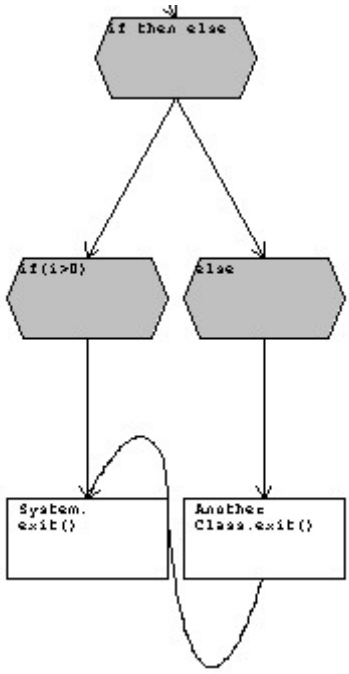

Figure 25: A selected part of the graph saved

ST-F-20 When printing a large graph, the graph was printed over several pages. Some of the pages were blank, but the whole graph was printed.

ST-F-21 The system has got a Windows-based user interface.

16 APPENDIX B

16.1 KNOWN PROBLEMS

In this section we present some shortcomings and problems in Annotert Kallgraf version 1.0.

16.1.1 Grammer/Parsing

Arrays
The brackets must be placed **after** the variable name, e.g. `int array[]`, and not `int [] array`. Both are allowed in Java, but the second will cause parse error in Annotert Kallgraf.

Switch-statements
Support is not implemented

Do-while
Support is not implemented

Comments
Using the comment construction:

```
/*******COMMENT******/
```

causes severe problems.
The use of one such comment line (a string with several stars on both sides) will be parsed as the start of a comment. This means that all code between two such lines will not be parsed, and any method invocation will be ignored. One such comment line outside a method (or another block) and one inside will cause a parse error, due to a missing brace ({ or }).

Special characters
The use of special characters will cause parsing error, e.g. $, @ and #.

16.1.2 Test Data Generation

- Generates data only for float, int and double variables in conditions
- Does not generate data for equality expressions (==), and inequality expressions(!=)
- Problems generating data for if-then-else with small changes in variables. The test data generator increments/decrements variable values by 1.0 when trying to fulfil conditions. When an increment/decrement of less than 1.0 is needed, as in example 12, the test data generator enters into an eternal loop.

12 Example

```
100  if(a > 0.2)
101    System.out.println();
102  else if (a > 0.1)
103    System.out.println();
```

```
104  else
105     System.out.println();
```

- Calculates the test coverage correctly only in basic examples

16.1.3 User Interface

- Problems previewing and printing large graphs (due to "out of memory exception" in the Java virtual machine)
- Problems saving large graphs as images (due to "out of memory exception" in the Java virtual machine)
- Positioning of large graphs is very time consuming and the system seems to "hang" during this operation
- Using the Java look and feel and JDK version 1.4.0 will cause exception during saving of an open analysis (probably a bug in Java and not the application).

17 APPENDIX C

17.1 IMPLEMENTATION OF THE REQUIREMENTS SPECIFICATION

In this chapter we present a table that shows which classes that implement the functional requirements presented in section 5.1. The table may be subject to discussion because of dependencies among classes. For example, requirement F-16 states that it must be possible to navigate horizontally in the call graph. This requires that the call graph already exists, but the classes responsible for this part of the system are not checked in the table. In general, we have checked those classes that are most important in fulfilling the given requirement. The parsing package is fundamental, and most functionality requires all these classes.

In the top row, the number of the functional requirement is found. The first column shows the packages and all their classes.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Parsing																					
Ylex	x				x	x							X	x							
PTParser	x				x	x							X	x							
PTNode	x				x	x							X	x							
PTUnaryNode	x				x	x							X	x							
PTBinaryNode	x				x	x							X	x							
PTTrinaryNode	x				x	x							x	x							
PTCompilationUnit	x																				
PTTypeDeclarations	x																				
PTClassDeclaration	x												x	x							
PTMultipleModifiers	x																				
PTModifier	x																				
PTClassBodyDeclarations	x												x	x							
PTFieldDeclaration	x												x	x							
PTVariableDeclarators	x																				
PTIdentifier	x																				
PTMethodHeader	x					x							x	x							
PTConstructor	x												x	x							
PTInnerClassDeclaration	x													x							
PTMethod	x					x							x	x							
PTMethodInvocation	x				x									x							
PTArgumentList	x													x							
PTIfThenStatement	x				x																
PTIfThenElseStatement	x				x																
PTForStatement	x				x																
PTWhileStatement	x				x																
PTMethodDeclaration	x					x							x	x							
PTBlockStatements	x																				
PTLocalVariableDeclaration	x													x							
PTBinaryExpression	x				x																
PTUnaryExpression	x																				
PTBlock	x																				
PTCatchClauses	x				x																
PTCatchStatement	x				x																
PTConstants	x																				
PTConstructorDeclarator	x												x								
PTConstructorInvocation	x												x								
PTFormalParameter	x																				
PTFormalParamList	x																				
PTLiteral	x																				
PTQualifiedName	x																				

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
PTTryCatchStatement	x				x																
PTVariableInitializer	x													x							
PTDeclarator	x																				
Visualization.Algorithms																					
ALGOSugiyama					x								x								
ALGODoubleArraySorter					x								x								
Visualization.GUI																					
GUIAboutDialog									x												x
GUIAppFrame								x	x				x	x		x	x				x
GUIClassListDialog			x	x					x												x
GUIDialog			x	x				x	x												x
GUIDrawGraph					x								x	x		x	x		x	x	
GUIDrawCallGraph					x		x							x		x	x		x		
GUIDrawClassHierarchyGraph					x								x			x	x		x		
GUIExitListener																					
GUIGraphs							x														
GUIHelp									x												x
GUIImageToClipboard									x												x
GUIIntFrame									x				x			x	x				x
GUIMenuAndToolBar			x	x			x	x	x	x	x	x	x			x	x				x
GUIOpenFileDialog		X							x			x									x
GUIPrintPreview									x												x
GUIProgressDialog								x	x												x
GUISetLookAndFeel									x												x
GUISplashWindow									x												x
GUITestDataDialog			x	x					x												x
GUITextFilter												x									
PackageInterfaces																					
GraphInterface	x		x	x				x					x	x	x			x			
VisualInterface			x	x				x					x	x		x	x				
Graph																					
Vertex	x		x	x	x	x							x	x	x			x			
GraphInformation	x		x	x	x								x	x	x			x			
Edge	x		x	x	x								x					x			
Graph.ClassHierarchyGraph																					
CHGClassNode	x												x								
CHGMemberVariable	x												x								
CHGMethod	x												x								
CHGConstructor	x												x								
CHGGraph	x												x								
Graph.CallGraph																					
CGCallGraph	x		x	x	x									x	x			x			
CGMethodInvocation	x				x									x	x			x			
CGConditionVertex	x				x																
CGInvocationVertex	x				x		x							x							
CGFormalParameter	x				x									x							
CGConditionString	x		x	x	x																
CGConditionParser	x		x	x																	
CGLocalVariable	x																				
The Util Package																					
UTILVariableStack	x													x							
UTILNodeVector	x												x	x							